The Effect of Vibrotactile Biofeedback Applied by a Vest on Human Postural Control

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MASTER'S THESIS

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M A S T E R ' S T H E S I S
for
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The Effect of Vibrotactile Biofeedback Applied by a Vest on Human Postural Control

Problem description:

Human body balance can be improved by light touch (<1N) with a static surface [2] as well as by being in light touch with another person [4]. However, in everyday life these methods are not always applicable, since 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 light touch. Consequently, wearable devices provide a good opportunity for people with postural instability for the application in everyday life [7]. Different devices have been investigated in research of postural control, located at different body parts [3, 6, 7, 8]. Moreover, various types of feedback have been used [8] and applied coupled [7, 10] or uncoupled [6] to the own body sway. When applying (vibro-)tactile feedback, not just the location of the tactile stimulus and the type of stimulus are important, but also what instruction is given to the subjects (to move towards the stimulus or away from it). Although, there is no consensus in literature [6, 7, 9, 1, 5] about how to give the instruction for improving postural control to be also more intuitive.Therefore in this study the following hypotheses will be examined:

1) Sway-dependent vibrotactile directional feedback applied to the upper torso positively influences postural control (lower body sway)

2) The type of instruction *repulsive*, *attractive*, or *no instruction* influences the effectiveness and intuitiveness on balance control.

As a secondary endpoint the relationship between Center of Pressure (CoP) and Center of Mass (CoM) data will be analyzed and discussed regarding the application in everyday life.

Tasks:

- Literature research and develop the study design
- Define the thresholds for feedback by pilot testing
- Adapt script for stimulus generation by the haptic vest
- Write/adapt scripts for communication and synchronisation of the different hardwares (haptic vest, force plate, IMU)
- Write/adapt scripts for capturing and saving data with IMU, force plate and sensor
- Carry out user study with 30 participants
- Data post processing and statistical analysis

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Abstract

BACKGROUND: Vibrotactile biofeedback can positively influence balance and consequently be helpful in fall prevention. Yet, it is unresolved whether attractive or repulsive stimuli (move in or in the opposite direction of feedback) are more effective for individuals. This study aims to investigate how a vest providing vibrotactile feedback influences postural control and which stimulus is more effective.

METHODS: The vest provides vibrotactile feedback in all four directions (anterior, posterior, medial and lateral) as well as in the diagonals based on tilt angles measured by an inertial measurement unit (IMU) at the lower back (L5). 30 young and healthy subjects were divided in three instruction groups (*attractive*, *repulsive*, or *no instruction* with attractive stimuli). After three baseline trials to determine the body sway threshold for vibrotactile feedback, we conducted four conditions (feedback on/off X narrow stance with head in the neck/semitandem stance) consisting of seven trials à 45 s. Root mean square (RMS) of position/angle deviation and standard deviation (SD) of velocity were computed for both center of pressure (COP) and L5 tilt angle. Additionally, percentage in time above threshold was calculated for L5. Mixed model analysis of variance (ANOVA) and t-tests with a significance level of .05 were used for statistical analysis.

RESULTS: In general, feedback decreased RMS of tilt angle, whereas RMS of COP was increased (for all $p < .05$). SD of velocity was increased for L5 and COP (for all $p < .05$). In the *attractive* and *repulsive* group feedback significantly decreased the percentage above threshold (for all $p < .05$), whereas in the *no instruction* group no differences were visible.

CONCLUSION: Real-time feedback provided by the haptic vest can reduce tilt at lower back, however, instructions on how to move are required.

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Chapter 1

Introduction

Falling can have serious consequences like loss of autonomy, and even death in the worst case [Wor08]. In younger adults falls can be mainly allocated to sports and vigorous activity with less consequences [TMWM05]. However, in older adults falling is of high concern as accidents obtain the fifth rank in leading causes of death after cardiovascular, cancer, stroke and pulmonary diseases. The majority of those deaths are due to falls (67 %) [RJ02]. According to the World Health Organization (WHO) 28-35 % of the people aged 65 and older fall annually [Wor08]. The influence of other diseases (e.g. osteoporosis), the degeneration of physiological processes (e.g. a slowing of reflexes) and little physical activity add to the high incidence of falls in elderly [RJ02, TMWM05]. Consequently, the prevention of falls is of great importance in terms of an aging population.

A possible explanation for the increased risk of falling while aging is the degeneration of sensory cues as vision, vestibular sensation, proprioception and tactile sensations, which can lead to an increased body sway [WJE11]. One possibility to counteract and prevent falls is balance training in the elderly [NDH14]. Additionally, several possibilities exist to improve balance immediately without training. For instance, the stabilizing effect of light touch (< 1 N) is sufficient to reduce postural sway, even though there is no mechanical support [RWLF01]. However, the application of light touch in everyday life is limited, since it is either stationary [RWLF01] or not enough nursing staff being available for applying interpersonal touch [JGGW09]. Furthermore, the use of classical walkers or robotic walkers [IDLN+19] is restricted, e.g. in small rooms or on stairs. Therefore, light wearable devices present a good opportunity for the application in everyday life to improve balance for people with postural instability [MWW+15]. Visual [AOCY16], auditory [FMF+13], electrotactile [VHF+11] and vibrotactile feedback [AOCY16, MWW+14] provide additional sensory information to improve postural control. Typically, such feedback devices give cues about sway in case certain thresholds are exceeded, as e.g. indicated by a force plate/pressure insoles or an Inertial Measurement Unit (IMU). Some studies have shown that this type of feedback can e.g. reduce Root Mean Square (RMS) of tilt angle [LKCS12, WWSK01] and Center of Pressure (COP) [WWSK01] as well as percentage in time spent above threshold [BCMS13]. In contrast to the other mentioned modalities, vibrotactile biofeedback is not distracting from other tasks [RMK+17], wearable [MWW+15] and unobtrusive [AOCY16] and consequently a promising approach in the fall prevention.

Yet, many possibilities exist to design vibrotactile feedback devices. In recent literature, mainly two [LKCS12] or four tactors [BCMS13] were used, whereby only one tactor indicated one specific direction (anterior, posterior, medial, lateral) [MWW+15, LKCS12, WWSK01]. Often, feedback was applied to the lower trunk [KVW03, BFC+20]. However, placing the motors on the upper trunk might enhance a faster processing, as they are closer to the cortical centres [NMAP+12]. Additionally, there is no consensus in which direction the feedback should be given. Should the feedback be applied in the direction you have exceeded a threshold or where you should move to? Recently, subjects were instructed to move in the direction of feedback [ABOY15, AEPY18] and it was shown that posture shifts towards vibrations if no instruction is given [LMS12]. For blind and visually impaired people navigation belts have been developed which give vibrotactile cues in the direction in which the movement should take place, e.g. turn left, consequently the left motor is switched on [AMS14, DGBRMPMD17]. Contrarily, in other studies subjects were explicitly instructed to move towards the opposite direction of the activated tactor [LKCS12,SBW12]. Further, this type of feedback was used to inform blind subjects about obstacles [KAR18].

This work aims to investigate how a vest providing vibrotactile feedback by four motors to the upper torso influences human postural control and what kind of stimulus is more effective and subjectively more intuitive in healthy young adults. Therefore, we compare three different types of instructions (*attractive*: move in the direction of feedback, *repulsive*: move in the opposite direction of feedback and *no instruction* with attractive stimulus).

To the best of our knowledge, this is the first study to compare attractive and repulsive stimuli in the research of vibrotactile biofeedback for improving balance. Additionally, to ensure that 1) vibrations are well sensed, 2) front and back sides are of the same perceived strength and 3) the intensity is equally perceived by all users, we individualized vibration frequencies rather than using fixed frequencies for all motors, which is often done in vibrotactile feedback devices [LKCS12, WWSK01]. Basing the vibration intensity on the individual vibration threshold is already commonly done in Stochastic Resonance (SR) stimulation [LLN+15, KKMM12]. Compared to previous studies, we provided feedback not only in either one or two axis, but in four axis including the diagonals. Therefore, two motors were active simultaneously to indicate movements in the anterior-posterior (AP) or medio-lateral (ML) axis (e.g. *repulsive* mode: if subjects sway towards the front, both front motors are active), compared to only one motor as in previous works. If sway exceeds the threshold in diagonal direction, only one motor is active (e.g. *attractive* mode: if subjects sway to the back right side, the front left motor is active).

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Chapter 2

Background

In this chapter, the state of the art related to light touch and different modalities for biofeedback to enhance postural control are described. Subsequently, several aspects on how to possibly configure a vibrotactile feedback device are elaborated. Lastly, human postural control is shortly explained as well as COP and Center of Mass (COM), which are quantitative measures to investigate postural control.

2.1 Light Touch for Improved Postural Control

The phenomenon of light touch represents one possibility to enhance postural control. Understanding the underlying mechanisms could be transferred to the design of a vibrotactile feedback device. Additionally, light touch and biofeedback can be compared in terms of their effectiveness. In the following, the principle of light touch, its mechanisms, and variations are described.

The last decades have shown that light touch with a stable object decreases postural sway during quiet standing [BAAF14, KM08]. Through light contact of the index finger with an external rigid and fixed object, additional sensory information is gained [BAAF14] (Figure 2.1). The contact force is less than 1 N and consequently not providing any mechanical support [AEPY18, JL94, KM08].

In the literature, two mechanisms of this effect have been discussed [CT15, KSL02]. On the one hand, according to the sensory hypothesis, the additional tactile input provides further reference and consequently helps to stabilize posture [LRD01, RWLF01]. On the other hand, Riley et al. [RSGT99] attributed the reduced sway to the implicit demand to keep the fingertip precisely at the fixed position and supported the suprapostural task hypothesis. Using this contact the kinematic chain between fingertip and trunk is stabilized and leads to less postural sway [RSGT99].
Recently, Chen and colleagues [CT15] investigated both mechanisms. According to their results, both explanations hold true, as light touch had a greater influence on postural stability rather than very light touch (< 0.5 N), which goes along with

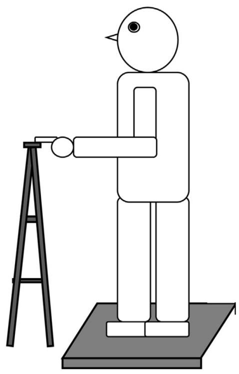

Figure 2.1: Light touch with a stable object [CT15].

the sensory hypothesis. However, also high precision, where subjects were asked to remain with their touch force as precisely as possible in the middle of the demanded range, led to a higher decrease in postural sway compared to low precision (supra-postural task hypothesis) [CT15].

The positive effect of light touch has not only been observed in healthy individuals but also individuals suffering from anterior cruciate ligament injuries [BGPB08] or with balance problems due to aging, brain lesion or other motor or sensory deficits benefit for their postural control [BAAF14]. This accentuates the potential of light touch in its further application for improving balance.

Recently, also variations of light touch have been investigated. E.g. Afzal and colleagues [ABOY15] used kinesthetic haptic feedback to the hand by a Phantom Onmi® haptic device to provide subjects with light directional forces based on sway to indicate how to move to regain balance. The output force was always less than 1 N. They showed reduced sway in young healthy subjects and stroke patients.
But also interpersonal light touch with another person to the index finger reduces postural sway. However, reductions were less compared to a fixed object in older adults [JGGW09]. Recently, it was shown that also robotic interpersonal light touch during maximum forward reaching is as efficient as human support for balance control [LKM+20]. Moreover, the support does not necessarily need to be applied to the hand. Contact with a reference at the leg or shoulder also reduced body sway [RWLF01].

This section demonstrated the beneficial effect of light touch in different populations. Whereas the coding of light touch is more natural and learned through previous experience (e.g. walking through a dark room), biofeedback substitutes and augments perception and might be more unfamiliar to humans [WWSK01]. A more detailed description of biofeedback for enhancing postural control is described in the following.

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2.2 Different Modalities of Biofeedback

Besides light touch, different types of biofeedback are used to improve balance. Typically, these devices consist of motion or force sensors to determine postural sway, a processor to calculate changes in sway and a feedback unit to inform the user about the actual sway [SBW12].
The goal of these devices is to improve balance through additional and enhanced sensory input [MWW+14, PWK06]. Furthermore, they can replace the information from an affected sensory system (e.g. vision or proprioception) [DTS+07]. They can either be used as real-time balance aid during everyday life or as a training tool for rehabilitation [SBW12]. The review of Ma et al. [MWL+16] has already shown that most of the devices are enhancing balance in healthy adults as well as in patients with balance diseases. However, it needs to be considered that such devices direct the conscious attention of the user to their own sway, which could negatively affect postural control. Recently, Chow et al. [CEY+18] showed that motor performance can be impaired by directing too much internal focus of attention towards the movements.
According to the feedback modality, the following biofeedback categories exist and are further introduced in the following: visual, auditory, electrotactile and vibrotactile [AOCY16, MWW+14]. In multimodal biofeedback different categories are combined. The next sections describe several studies to demonstrate the beneficial effect of the different modalities in various populations and set-ups. Moreover, their advantages and drawbacks are outlined. Especially the studies related to vibrotactile feedback are important for the design of our vibrotactile vest and the set-up of the study. Additionally, our results can be classified and compared with these publications.

2.2.1 Visual Biofeedback

Visual feedback systems have been used in training [EVB+12, NKIF10, AMM+18] as well as for real-time feedback [JTL16, KHG93].
Nitz et al. [NKIF10] and Esculier and colleagues [EVB+12] showed that a training intervention with the Wii Fit™ tool can improve balance parameters as indicated by balance tests (e.g. Community Balance and Mobility assessment, unilateral stance) in healthy women and subjects with Parkinson's disease. The tool provides visual feedback by a marker on the screen, which shows the movements of the subject for most of the activities. Subjects can win points during the task if the marker is kept within a certain area [EVB+12].
In the study of Anson et al. [AMM+18] older adults with self-reported balance problems improved their dynamic balance as indicated by the Balance Evaluation Systems Test (BESTest) (after training consisting of walking on a treadmill). While walking individuals received visual feedback by a moving cursor displaying the trunk motion on a bulls-eye [AMM+18].
But also real-time visual biofeedback helped young adults to reduce Standard De-

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viation (SD) of COP during quiet standing. They were instructed to minimize the movements of the visual target displaying their COP [JTL16].
Krizková et al. [KHG93] provided subjects with visual feedback of their COP movements in ML and AP directions. Subjects were instructed to maintain a light point, representing their position, within an encircled area. With visual feedback the mean amplitude of body sway was reduced. Additionally, power spectrum density of stabilograms showed a decrease in the frequency range below 0.05 Hz and an increase in the frequency range of 0.4 to 1.5 Hz. Furthermore, mean velocity was increased.

Even though all these studies showed that visual feedback can positively influence balance, a wearable design is difficult to imagine with visual biofeedback as a display is required, which is unsuitable for everyday use [AEPY18]. Furthermore, following a moving target can induce dizziness in patients with vestibular diseases. A further drawback of this modality is that it can only be used with open eyes and when the head position is not changing [BCMS13].

2.2.2 Auditory Biofeedback

Audiobiofeedback (ABF) devices are deployed for real-time feedback [CCP+18, CDC+05,DCH05,DHC07,FFG+13,FMF+13] as well as in training [MHN+11,NMH+10]. In this section, first, real-time feedback devices tested in healthy subjects, then, in older or diseased subjects are introduced. Finally, two training interventions are presented.

Chiari et al. [CDC+05] tested their audiobiofeedback (ABF) system, consisting of an acceleration sensory unit and headphones, in healthy subjects. A dead zone, where no feedback is provided, is defined by considering the subject's height. While sway is in this area, subjects hear a pure tone. As soon as this area is exceeded different tones were sent. The ABF system led to improvements in balance, especially in more challenging conditions (standing on foam or with closed eyes).
The components (sensory input unit, processing unit and sensory output unit) of the iBalance-ABF of Franco and colleagues [FFG+13] to improve balance in the ML axis are embedded into a smartphone. A sound to the left or right earphone is present in case trunk tilt exceeds the dead zone, where no feedback is provided. The stimulus is repulsive, hence, the subjects need to move away to correct posture. Young healthy individuals reduced sagittal trunk tilt through this ABF [FFG+13].
Fleury et al. [FMF+13] tested the same iBalance-ABF in older healthy subjects. The additional information helped older adults to significantly reduce ML trunk sway in tandem stance.
The system of Constantini et al. [CCP+18] consists of an IMU, a processing unit and a headphone audio device and provided subjects with audio-feedback signals related to the equilibrium. A pleasant tone is generated in a stable position, whereas the sound becomes increasingly bothering when being unstable. Body sway was

reduced when the ABF was available. The effectiveness was higher in younger people compared to older participants, maybe due to a higher reactivity to feedback and faster adaptation to multimedia stimuli [CCP+18].
The studies of Dozza and colleagues [DCH05, DHC07] demonstrated that auditory biofeedback can also be efficient in diseased individuals. The ABF system uses earphones and an acceleration sensor near COM to capture accelerations in AP and ML axes. After exceeding baseline sway $\pm 1°$ the sound changes pitch or volume. The ABF reduced postural sway during quiet standing and was more effective in subjects with bilateral vestibular loss and in case of limited sensory input (standing on foam or with closed eyes) compared to control participants [DCH05, DHC07].

The following two studies showed that auditory cues can help individuals with Parkinson disease [MHN+11] and progressive supranuclear palsy [NMH+10] to improve their balance by a six-week intervention program.
Tri-axial accelerometers and gyroscopes are attached near COM. The auditory feedback is modulated in frequency and amplitude by the trunk acceleration in ML and AP directions. Exercises related to posture and balance were selected for each participant individually [MHN+11, NMH+10]. The intervention led to a significant improvement in balance as measured by the Berg Balance Scale in subjects with Parkinson disease [MHN+11].
Nicolai and colleagues [NMH+10] used the same ABF in patients with progressive supranuclear palsy. Again, a significant improvement in the Berg Balance Scale was observed.

All these ABFs have the advantage of being low-weight, low-cost, compact and non-intrusive and consequently offer the possibility of being employed as wearables in everyday life [CCP+18, AEPY18, AOCY16]. The feedback is private as it is normally played via headphones or earbuds. However, this might also lead to missed environmental cues (e.g. traffic sounds) or commands of the therapist [AEPY18, RMK+17].

2.2.3 Electrotactile Biofeedback

Electrotactile constitutes a further modality for applying biofeedback. All publications related to electrotactile feedback applied the stimulation to the tongue. Several studies investigated the BrainPort® balance device (Wicab, Inc) in different settings [BBD10, BB11, DTS+07, GBPP13, VHF+11, VPC+08], whereas Vuillerme et al. [VCP+07, VCP+08] introduced and evaluated another biofeedback system.

The BrainPort® balance device includes an accelerometer determining head orientation in AP and ML axes and an intraoral device, which consists of a plate of electrodes and is placed on the top and front part of the tongue (Figure 2.2) [BBD10, DTS+07]. Patients need to centralize the electrotactile stimulus to be balanced [BB11]. A

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stimulus on the left side of the tongue means that subjects need to move to the right and vice versa [DTS+07]. In the following, studies investigating the training effects of BrainPort® in diseased subjects are described as well as the effectiveness of real-time feedback by this device.

Figure 2.2: BrainPort® Balance Plus [Wic20].

Several studies examining the effectiveness of BrainPort® focused on training patients with balance diseases.
In the study of Barros and colleagues [BBD10] bilateral vestibular loss patients trained over two weeks with the device. Subjects significantly improved postural control measured by the Sensory Organization Test (SOT).
A three-week training with patients suffering from central imbalance led to an improved Balance Index (BI) indicated by Computed Dynamic Posturography (CDP) and a subjective feeling of an increased stability [BB11].
Even a training intervention of three to five days can lead to statistically improved balance amongst others indicated by the SOT via CDP in subjects with balance dysfunction [DTS+07].
Similarly, Ghulyan-Bedikian et al. [GBPP13] trained chronic vestipulopathic patients over four days. They reported a significant improvement of posturographic scores in older subjects and patients with severe vestibular loss benefiting to a greater proportion.
Vuillerme et al. [VPC+08, VHF+11] used the BrainPort® for real-time feedback. First, they showed the effectiveness in young and healthy adults. When using the device, surface area and the length of COP displacement in AP and ML directions were reduced [VPC+08]. In unilateral vestibular-defective patients these benefits were replicated. They showed a reduced COP area on a firm as well as on a foam surface, with the improvements being higher during the instable condition [VHF+11].

Additionally, Vuillerme and colleagues [VCP+07, VCP+08] investigated a further device. It consists of a tongue display unit providing electrotactile output by an array of 6x6 electrodes. Based on a pressure mat, COP data are calculated and serve as the basis for the feedback. The feedback is repulsive, e.g. sway towards the right side is presented by a stimulus to the right side of the tongue [VCP+07, VCP+08]. Both studies, conducted with young healthy adults, demonstrated the effectiveness

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of the device by a smaller surface area [VCP+07] and a decreased SD and range of COP displacements [VCP+08].

Electrotactile devices offer the advantage of being lightweight and portable [GBPP13]. Additionally, the tongue is an organ of many nerve fibres, high sensitivity [BBD10] and connected to important structures in the brain stem [BB11]. Furthermore, only low voltage and current is required due to the presence of the saliva, which is electrolytic and ensures good contact between the tongue and electrodes [VPC+08]. The fact that the device is placed in the mouth makes it aesthetically acceptable [VPC+08]. On the other hand, talking and eating is complicated or impossible [JSA+10].

2.2.4 Vibrotactile Biofeedback

Vibrotactile biofeedback follows the concept of light touch. The forces provided are not giving mechanical support to the receiver but they are perceived by the somatosensory system [AEPY18]. As the state of the art is of high importance for this work, in this section only a short description is given, more details are presented in section '2.3 Configuration of Vibrotactile Biofeedback'.
First, studies related to healthy subjects are presented [BFC+20, LMS12, WWSK01], followed by studies related to older [MWW+15, LWL+15] and diseased patients [KVW03, JSA+10, LKCS12, NMAP+12]. Lastly, a training intervention with vibrotactile feedback is shown [BCK+18].

The following studies refer to the effects of real-time vibrotactile feedback in healthy subjects. Ballardini et al. [BFC+20] compared different encoding modes ('always on', 'dead zone' and 'sham') amongst healthy young subjects. Feedback synchronized with acceleration data of L3 led to a decreased amplitude of acceleration indicated by the RMS mainly in AP directions, in which feedback was applied. No differences were found for the modes 'always on' and 'dead zone', whereas 'sham' feedback increased the RMS of acceleration in AP.
Wall et al. [WWSK01] investigated differences between a shoulder and a side placed vibrotactile device providing feedback in the ML axis as well as light touch in healthy young adults. Reference for the feedback is an accelerometer and a gyroscope at the head. Additionally, COP trajectories were measured. Both vibrotactile feedback devices decreased RMS of head tilt and COP. Light touch led to the smallest amount of RMS of COP, but the highest values of RMS of head tilt.
The study of Lee and colleagues [LMS12] is a little bit out of sequence. They investigated whether subjects responded to stimulations. Consequently, vibrations were not coupled with the sway of the subjects. Following the vibration RMS of sway in AP and ML directions was increased for internal oblique and erector spinae muscles, but not for external oblique as indicated by an IMU. Posture shifted in the direction of the vibration. No changes in COP were evident.

The next two studies compared the outcomes of young and old individuals while using vibrotactile feedback. Healthy young and elderly subjects decreased sway parameters (amongst others: RMS distance, range of COP in ML and AP, 95 % confidence ellipse area) when using vibrotactile feedback to the upper body referenced to force sensor insoles [MWW+15].
Lin et al. [LWL+15] investigated the age effect while using vibrotactile feedback. Overall, older subjects showed greater RMS of COP and RMS of trunk tilt values compared to young subjects. Additionally, vibrotactile feedback led to a significantly higher RMS of COP in older adults, whereas there was no change in young adults in the fixed platform condition.

The following studies demonstrate the beneficial effect of biofeedback devices in diseased individuals. Kentala et al. [KVW03] showed that vibrotactile feedback to the lower torso helped adults with balance dysfunction to improve their balance. Body tilt in AP axis was reduced as well as their SOT5 and 6 scores.
Furthermore, in patients with severe bilateral vestibular loss sway path was decreased due to vibrotactile biofeedback to the waist when the sensor was placed at the head. Positioning the sensor at the trunk was not as effective [JSA+10]. However, the improvement was not solely induced by the feedback, but also by training, increased self-confidence and alertness.
Lee and colleagues [LKCS12] investigated healthy young adults and subjects with vestibular deficits. Feedback of a cell-phone based feedback device amongst others significantly reduced RMS of sway in ML, elliptical area and the percentage within the no feedback zone in both groups. Specifically, healthy subjects reduced RMS of tilt in AP and ML axes during Romberg and tandem Romberg stance, whereas in semitandem stance tilt decreased only in ML directions. Diseased subjects only performed semitandem stance and decreased RMS tilt only in ML directions.
In subjects with Parkinson disease, one training session with vibrotactile feedback of the BalanceFreedom™ (see section '2.2.5 Multimodal Biofeedback') led to significantly greater decreases in roll and pitch sway angular velocity compared to the control group. Furthermore, the feedback group showed greater training effects indicated by a greater increase in roll sway angle in controls after the training session [NMAP+12].

Vibrotactile feedback not only leads to improvements in real-time applications but also following a training intervention. Training over eight weeks (three times for 45 minutes per week) in healthy older adults showed beneficial effects for balance of the experimental group receiving feedback compared to a control group. Clinical balance tests were used to investigate performance. The experimental group showed significantly higher improvements in SOT and mini balance evaluation systems test [BCK+18].

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All of the above-mentioned studies demonstrated balance improving effects of vibrotactile feedback. Those studies solely referred to quiet standing. However, there is also evidence that vibrotactile feedback improves balance after unexpected perturbations [GSL12, LMTL17, ML17, SBW12] or during walking [JPA$^+$12, SBOW13, Wal10, WWS09]. Our work only refers to quiet standing, consequently, those studies are not described in more detail.

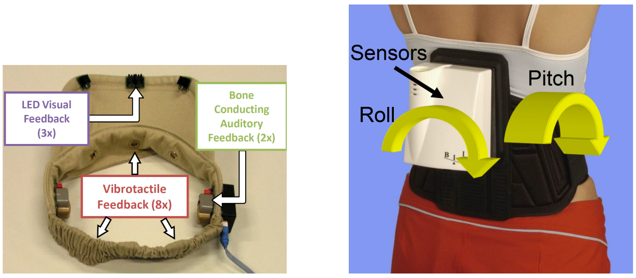
Vibrotactile feedback offers the advantage of not distracting from other tasks or observing the environment [AOCY16, RMK$^+$17, WWSK01]. Furthermore, it is unobtrusive [AOCY16] and only perceived by the individual wearing the device [RMK$^+$17]. The devices are portable and convenient [MWW$^+$15]. Additionally, vibrations can be applied to different body parts to take other circumstances into account. E.g. if the hands are occupied by other tasks, the feedback can be given to the head [RMK$^+$17]. Lastly, the feedback is very intuitive and already applied in military contexts for navigation and in blind people for orientation purposes [JSA$^+$10].

2.2.5 Multimodal Biofeedback

Multimodal biofeedback exists in different combinations. Some systems combine two modalities [AOCY16, AOY15, MM11, BCMS13], whereas the BalanceFreedom™ system incorporates three [DCT$^+$10, HHv$^+$13, LHD$^+$16, HNAA10].

The following studies address two modalities. Afzal et al. [AOCY16, AOY15] combine visual, provided by a circle on a screen, and kinaesthetic biofeedback by a Phantom Omni®. Torso tilt for reference is measured by a smartphone. In healthy young subjects the different feedback types (haptic, visual and multimodal) were superior compared to no feedback in terms of body sway, especially multimodal feedback.
Milosevic and colleagues [MM11] combine audio and visual biofeedback for real-time application referenced to an accelerometer in healthy subjects. The visual feedback illustrates the performance on the balance board, whereas sound cues indicate directions. The higher the sound, the higher the deviation in that direction. Postural performance was significantly improved by the feedback with a smaller variability of balance board movements.
In the study of Bechly and colleagues [BCMS13] visual and vibrotactile biofeedback are combined and compared between subjects with peripheral vestibular deficit and age-matched controls. The feedback is based on an IMU. Vibrotactile feedback is given by four tactors to the trunk, whereas visual feedback is displayed on a screen by four red squares. A filled square stands for an exceeded threshold. All feedback modalities (visual and vibrotactile) as well as multimodal biofeedback improved balance performance (mean and variability of ML trunk tilt) in both groups compared to baseline.

The BalanceFreedom™ system addresses three modalities and combines vibrotactile, auditory and visual biofeedback based on the angular displacement of the trunk measured by a SwayStar™ consisting of angular velocity sensors (Figure 2.3). Activation thresholds are set individually with the vibrotactile feedback to the head in the direction of sway (repulsive) being activated first, followed by acoustic and finally, the visual signals as a flushing lights [DCT+10, HHv+13, LHD+16].



(a) (b)

Figure 2.3: a) BalanceFreedom™ and b) SwayStar™ [LHD+16].

The following studies demonstrate the beneficial effect of the real-time feedback by the BalanceFreedom™ in healthy and diseased subjects. Lastly, one training intervention with the device is presented.
Davis et al. [DCT+10] compared the outcome of healthy older adults compared to younger ones. Biofeedback significantly reduced angular displacement of the trunk in both populations, in some cases only the balance of the elderly was influenced.
Huffman et al. [HNAA10] compared the effects of biofeedback in either AP or ML axes in healthy young adults. Biofeedback reduced sway angle and increased sway angular velocity. Both directions of feedback showed a greater influence in the roll direction, whereas AP feedback was very efficient for reducing pitch angle.
Furthermore, bilateral peripheral vestibular loss patients reduced their pelvis sway angle displacements with feedback to the values of healthy controls in tasks with eyes open or closed on foam or normal surface. Furthermore, it was obvious that feedback induced an improvement in antagonistic muscle synergies at the lower extremities and the trunk [HHv+13].

Lim and colleagues [LHD+16] compared the outcomes of training with the BalanceFreedom™ system to training without feedback system in healthy older adults in stance and gait tasks. Balance performance as indicated by pitch and roll angular displacement was slightly improved by training with biofeedback.
Advantages and disadvantages already presented for the different modalities also apply for multimodal biofeedback. The next section describes another phenomenon, the Stochastic Resonance (SR) stimulation showing also promising results for improving postural control.

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2.2.6 Excursus: Stochastic Resonance Stimulation

Beside light touch and biofeedback, it has recently been shown that stimulations of so-called noise can positively influence balance [SD18, ZLP+18, LLN+15]. Here comes Stochastic Resonance (SR) stimulation into play. This phenomenon is described in the following section as well as some studies related to it.

The concept of SR stimulation describes a phenomenon where the presence of noise improves the detection of low-level stimuli in a non-linear system [SD18, WBT+18, CIG96]. Obviously, the amplitude of those stimuli is of great importance in the application [SGD18]. Normally, they are below the detection threshold [ZLP+18, LLN+15, KKMM12]. The SR-effect can be visualized by an inverted U-shaped curve between the performance measure and the intensity of the stimulus [SD18, KKMM12]. At first, increasing the noise leads to improved performance in the non-linear system. However, as soon as the noise becomes too high, this beneficial effect disappears [KKMM12].

Mostly, SR-methods are applied either by mechanical [SGD18, LLN+15, PNS+02, PNH+03, KKMM12]) or electrical current [SD18, ZLP+18] stimulations. Some studies related to both types are presented in the following.
Insoles with piezoelectric actuators for generating vibrations were tested by Lipsitz et al. [LLN+15] in healthy older subjects. The vibration threshold was measured by a Method of Limits (MOL) approach (see section '2.3.4 Determination of the Vibration Threshold'). Noise at 70 % as well as 85 % of vibration threshold reduced elliptical area and sway in ML directions compared to no stimulation.
Priplata et al. [PNS+02] also applied stimulations to the feet. They used a platform with mechanical actuators. The intensity was adjusted by the subjects until they could no longer feel the noise signals. Stimuli at 90 % of the vibration threshold reduced postural sway (e.g. radius, area, range) indicated by a stabilogram of shoulder displacements in young and older subjects, whereby the elderly seemed to benefit more.
In another investigation of Priplata and colleagues [PNH+03] gel-based insoles with tactors under the forefoot and heel were studied in young and elderly subjects. Again, the intensity was adjusted by the subjects themselves and the level was set to 90 %. Stabilograms indicated a greater improvement in elderly, as all sway variables (amongst others mean radius, area, range in AP and ML) were reduced and only some variables in young adults.
Kimura et al. [KKMM12] demonstrated that stimulations of a mechanical oscillator to the index fingertip at 50 % of vibration threshold in young and healthy subjects significantly reduced mean velocities in AP and ML directions compared to no stimulation (light touch) and 100 % of vibration threshold. A MOL approach was used to determine the vibration threshold.

On the other hand, Sacco et al. [SGD18] showed that vibrations of different strength (sub- and suprasensory) applied to the Achilles tendon may only improve accuracy during an active postural positioning task but not in quiet standing indicated by an unchanged COP absolute velocity in young and healthy subjects. To determine the sensory threshold a MOL approach was used. The mean of five repetitions of increasing and decreasing the stimulus was calculated as threshold.

In the following, two studies using electrical stimulations are described. Severini and colleagues [SD18] applied low-level electrical white Gaussian noise current stimulations (no stimulation, 70 %, 90 %, 110 % and 130 % of the sensory threshold) to the tibialis anterior muscle of the standing leg during single-leg stance. Stimuli of 15 seconds were supplied and increased in case they were not perceived until they were felt to determine the sensory threshold. Most balance parameters (e.g. path length, range) were reduced by subsensory stimulation, whereas suprasensory stimulation increased sway in healthy subjects.
Zarkou and colleagues [ZLP+18] compared children with cerebral palsy and controls during quiet standing with electrical SR stimulation. Stimuli were applied to the ankle muscles and ligaments (lateral soleus, peroneus longus, and tibialis anterior muscles and anterior talofibular and deltoid ankle ligaments). The sensory threshold was determined by a MOL approach, which was repeated for four increases and decreases. The lowest value was taken as reference. Children with cerebral palsy reduced sway parameter (e.g. COP velocity, COP area) to a greater amount compared to healthy controls.

The above-mentioned studies indicate that SR stimulations can contribute to enhanced postural control. For the further development of vibrotactile devices, it is thinkable to use this concept additionally. The following chapter focuses on several aspects which need to be considered in the development process of a vibrotactile biofeedback device.

2.3 Configuration of Vibrotactile Biofeedback

Vibrotactile biofeedback devices consist of three main components: 1) a vibrotactile display, 2) a sensing unit to detect body sway, and 3) a processing unit [JSA+10, KVW03, MWW+15]. In the following, the major focus lays on the vibrotactile display and its configuration (direction of the feedback and the instructions to the subject), as well as on the motors for the vibrations and their location. Consequently, it is also shortly described how the human skin receives such stimulations. Then, several methods for determining the vibration threshold are presented. Moreover, different possibilities for the sensing unit are shown as well as how the body sway threshold for feedback onset can be defined. The processing unit is not part of this review as it is not of high importance for the design. Lastly, it is briefly elaborated which trial

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duration is recently used in other publications for testing the effects of vibrotactile real-time feedback.

2.3.1 Instructions and Direction

Biofeedback devices can differ in terms of the direction of their stimulations. When looking into the literature of biofeedback, it is apparent that there is no consensus, yet, in which direction the feedback should be given to be the most effective. Repulsive as well as attractive stimuli have been used. Additionally, navigation devices for visually impaired individuals use vibrotactile feedback to indicate directions. Consequently, their results and research are considered as well.

First, it needs to be mentioned that some studies did not explain whether they were informing participants about the feedback [WWSK01] or gave no information about the feedback, but provided subjects with a familiarization period [BFC+20].

Attractive Stimuli
In the studies of Afzal et al. [ABOY15, AEPY18] subjects needed to move in the direction of the feedback to regain balance, regardless whether they used the Phantom Omni® held in the hand [ABOY15] or a wearable reaction wheel-based system at the back of the individual for kinesthetic haptic feedback [AEPY18]. Both approaches were promising for balance improvements as indicated by the mean velocity displacement [ABOY15] or RMS of trunk tilt [AEPY18].
An argument which speaks in favour of attractive cues is the fact that those are used as turning guidance in navigation tasks [LS11]. Furthermore, Lee et al. [LMS12, LMS13] demonstrated that stimulation over internal oblique and erector spinae muscles led to shifting of posture in the direction of the vibrotactile cues, while subjects were unaware concerning the vibrations and their duration.

Repulsive Stimuli
Repulsive stimuli can be understood in the way of encountering an obstacle and consequently moving in the opposite direction of the feedback [WWSK01]. These stimuli can also be more intuitive in the way of guiding the patient like a therapist to the desired position in motion replication tasks [LS11].
Several studies explicitly instructed subjects to move in the opposite direction of the biofeedback. An overview of the instructions and the corresponding studies is displayed in Table 2.1.
Additionally, it needs to be mentioned that studies using electrotactile feedback use repulsive cues without exception [VCP+08, BBD10, GBPP13].

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Table 2.1: Instructions for repulsive stimuli.

Paper	**Instruction**
[BCMS13]	All modalities provided feedback in the direction of tilt and activated only when body tilt approximately exceeded a 'no feedback zone' threshold of 1° in that direction.
[FFG+13]	'Repulsive' ABF instructional cueing.
[JSA+10]	One actuator was activated in the direction of a patient's body tilt if it exceeded a tilt magnitude of 2°.
[LKCS12]	Subjects were instructed to move away from the vibrotactile cue.
[LWL+15]	The subjects were instructed to reduce the vibration as much as possible by moving in the opposite direction.
[MWW+15]	They were instructed to move towards the opposite direction of the vibrator that was activated.
[NMAP+12]	The subject was asked to correct sway by moving the trunk away from the direction indicated by the vibrator.
[SBW12]	Subjects were instructed to move to null out the vibrations.
[SBOW13]	Subjects were instructed to move in the direction opposite to the vibration to correct trunk tilt.

Attractive vs Repulsive

In a different context, the outcome of attractive and repulsive stimuli has already been compared by Lee and colleagues [LS11]. Specifically, they used a Mobile Instrument for Motion Instruction and Correction (MIMIC) to transmit movement cues of a therapist performing trunk tilt to a patient via vibrotactile feedback. Smallest tilt errors and greatest correlations between patient and therapist occurred in the presence of repulsive cues.

To get a more profound understanding of this topic, it is now described, how navigation belts work in this sense as they are also designed to indicate directions.

Navigation belts

Assistive navigation devices, especially navigation belts worn around the waist, for blind people also make use of vibrotactile feedback. There, mainly attractive cues are used:

Adame et al. [AMS14] investigated their simple kept system with just four motors. In case the user needs to turn e.g. to the left, the left motor is switched on. They concluded that the device is efficient for the guidance of blind people.

Bharadwaj et al. [BSG19] used a slightly different arrangement. Five pairs of two motors are attached to the waist with the middle part being placed on the umbilicus. A vibration from the umbilicus travelling to the right side indicates that a turn to the right is appropriate. It was concluded that the hip-worn belt is especially promising in noisy environments.

The belt of Heuten and colleagues [HHBP08] consists of six motors equally distributed

around the waist and aims to guide and keep users en route. In case subjects deviate to the left side, the right motor is activated. Using their device made it possible for users to stay within a specified corridor while walking through an unknown path.
The belt of Durá-Gil et al. [DGBRMPMD17] uses four front motors for indicating the direction, whereas the four back motors indicate that stopping or slowing down the velocity is required. Again, activated motors on the left side aim to guide the user to turn left. The belt can be used as an aid for guiding blind people on athletic tracks.

Katzschmann and colleagues [KAR18], however, indicate obstacles by strong frequent pulses on the side of the obstacle. Consequently, users need to move away from the vibration to avoid the obstacle. Stairs and obstacles in front of the user are specified by different rhythms of pulses. The belt consists of five motors. They found evidence that the belt provoked less collisions compared to a white cane in blind users but task completion took more time. This could be allocated to the fact of an insufficient amount of training with the device.

Overall, it can be summarized that there is no consensus in the literature, yet, which type of instruction is superior and more intuitive for the user in the field of biofeedback. A further aspect to consider are the motors used to apply the vibrations, which are described in the upcoming section.

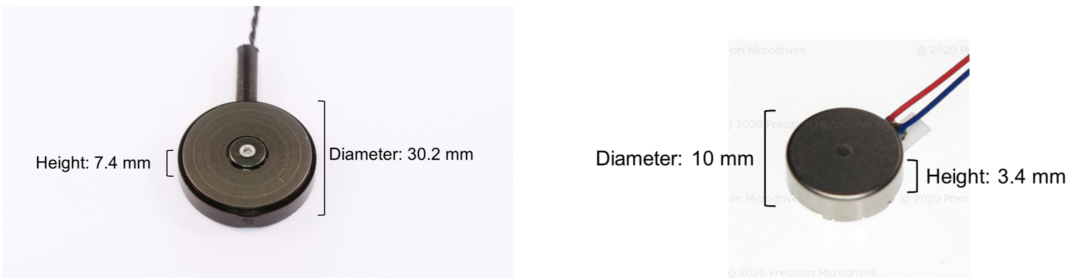
2.3.2 Motors, their Positioning and Frequency

This section aims to present different motors for applying vibrotactile feedback. Then, different locations for positioning these motors are discussed as well as their number and their vibration frequency.

Motors
Different types of motors are available on the market. Recently, often C-2 tactors (Engineering Acoustics, Inc., USA) [BCMS13, LMS12, LWL+15] have been used in the research area of vibrotactile feedback.
C-2 tactors are linear actuators, which consist of a contactor (Figure 2.4(a)). Current induces oscillations of the contactor perpendicular to the skin, which leads to point-like sensations on the skin [Eng20]. They offer the advantage that frequency and amplitude can be controlled independently [RMK+17].
However, those motors have a high power consumption and are expensive, e.g. one C-2 motor costs approximately $ 250 [LKCS12]. Eccentric Rotating Mass (ERM) vibration motors represent a cheaper alternative [SPW+15]. They need low energy and are lightweight [SPW+15]. E.g. Precision Microdrives Inc. (London) offers them for less than 10 € [Pre20a].

ERM vibration motors are usually Direct Current (DC) motors, which consist of an eccentric mass placed on the shaft of the motor [MZC07] (Figure 2.4(b)). Electric

current leads to rotations of the shaft and consequently causes vibrations [CDC12]. Mass of the motors can either rotate orthogonally (cylindrical motor) or parallel (pancake motor) to the skin [MZC07]. It is important to know that frequency and amplitude are proportionally coupled with the current in ERM motors and consequently cannot be controlled individually [MZC07, CDC12].
Motors of Precision Microdrives are implemented in the feedback devices of Ballardini and colleagues [BFC+20] and Bao and colleagues [BCK+18]. Further research groups use this type of motor from different or unspecified manufacturers [JSA+10, LKCS12, MWW+15].



(a) (b)

Figure 2.4: a) C-2 tactor [Eng20] and b) ERM motor of Precision Microdrives [Pre20b].

Positioning
When reviewing the previously described literature (see section '2.2.4 Vibrotactile Biofeedback') concerning vibrotactile feedback in terms of the positioning of the motors, it becomes evident that they are either placed on the lower torso [BFC+20, BCK+18, LMS12, JSA+10], the upper torso [MWW+15] or the head [NMAP+12]. The number of motors indicating the direction also differs amongst studies, with some using two [BFC+20, LKCS12], four [BCK+18, BCMS13], six [LMS12] or even twelve [JSA+10].

The following studies used different numbers of motors, but all attached them to the lower torso. Ballardini et al. [BFC+20] placed one motor at the abdomen and one at the back at L5 level. Kentala and colleagues [KVW03] also located the tactors at the front and back, however, they used an array of three tactors at each location (Figure 2.5(a)). For the height of the motors, Lee et al. [LKCS12] took L4/L5 as reference. For Romberg stance motors were placed on the trunk midline (navel and spine) and for semi-tandem Romberg and tandem Romberg stance on the left and right side of the torso. By this set-up, feedback could only be given in one axis, either AP or ML [LKCS12].
There are also studies using four motors to be able to indicate four directions. Bao and colleagues [BCK+18] as well as Bechly et al. [BCMS13] placed the tactors

over the navel, lumbar spine and left and right sides. In the study of Lin and colleagues [LWL+15] two motors were placed above each other, with a distance of 5cm at the same locations as mentioned before.
Lee et al. [LMS12] placed six motors over the left and right internal oblique, external oblique, and erector spinae muscle at the height of L4/L5 resulting in skewed movements (Figure 2.5(b)). Janssen and colleagues [JSA+10] even used twelve motors distributed around the waist (Figure 2.5(c)).

The following studies attached the tactors to the upper torso. Ma et al. [MWW+14, MWW+15] placed the motors at the anterior (manubrium), posterior (first thoracic level), left and right (acromion) side of the upper trunk each corresponding to one direction (Figure 2.5(d)).

Wall et al. [WWSK01] investigated tactors on the shoulder as well as at the left and right side of the trunk and found improvements for both locations (Figure 2.5(e)). However, it needs to be mentioned here that the coding schema is different. For the shoulder, pulse rate increased in case of increasing sway, whereas at the sides, the number of tactors increased.
A further possibility for placing the motors is the head [NMAP+12] (Figure 2.5(f)). Here, again, feedback can be given in all four directions.

Overall, several aspects need to be considered when deciding for the positioning of the motors. The sensing unit and the vibrotactile display need to be placed with adequate distance to avoid interference [BFC+20]. Furthermore, positioning influences the processing velocity. If the stimulations are applied close to the head, information reaches the brain faster [RMK+17].
Additionally, the sensitivity of the body part needs to be taken into account. Tongue, head and fingers have a high spatial resolution, however, they are not linked to balance and are often engaged in other tasks [LKCS12, HVJ+18]. On the other hand, the trunk is less sensitive, especially in the abdominal region [Wil54], and the tactile sensation at the back of the trunk is lower compared to the front in healthy men [KK17]. However, the trunk is directly related to the location of COP and COM and consequently might be more effective for balance control [LKCS12, KSL02]. Moreover, the upper torso, e.g. the sternum, has the lowest threshold for detecting vibrations over the torso [Wil54].
Sensitivity is not only influenced by the location of the stimulus [STS+03] but also by sex [KK17], age [STS+03, GBWT18, TM81], temperature [MZC07], diseases [COB+14], the configuration of the stimulus (e.g frequency, duration) [MZC07] and Body Mass Index (BMI) [DSEB16].

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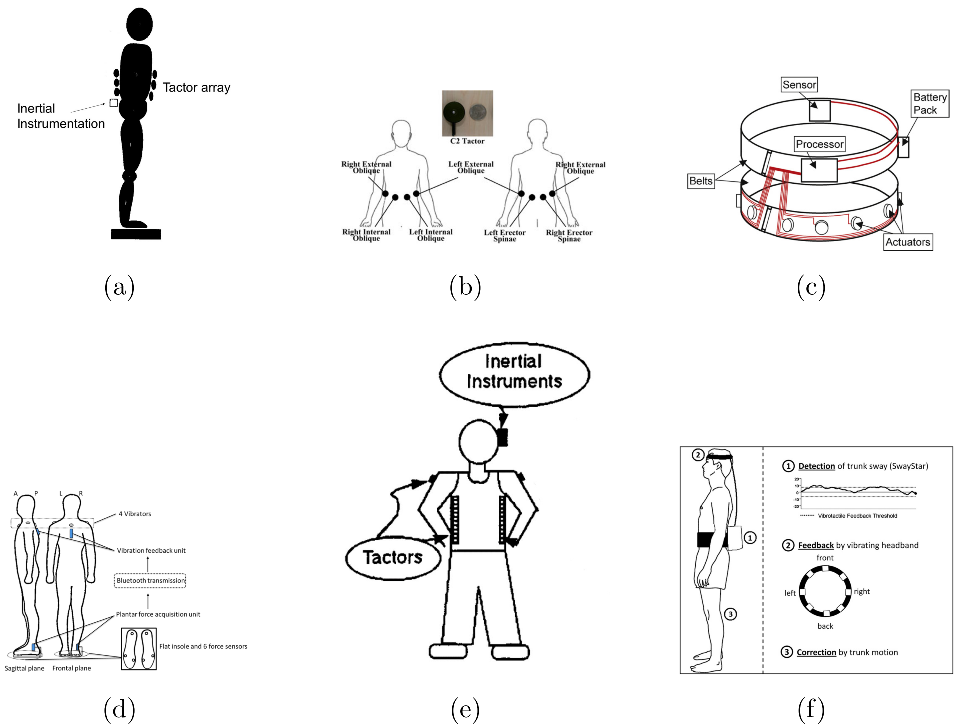

Figure 2.5: Examples for the motor positioning in vibrotactile displays. a) Kentala et al. [KVW03], b) Lee et al. [LMS12], c) Janssen et al. [JSA+10], d) Ma et al. [MWW+15], e) Wall et al. [WWSK01] and f) Nanhoe-Mahhabier et al. [NMAP+12].

Frequency

The frequency of the vibration can be used to convey information to the subject [LS11]. Therefore, this parameter needs to be taken into account when designing vibrotactile feedback. It is important that the vibrations can be well sensed by the human skin (see section '2.3.3 Excursus: Mechanoreceptors of the Skin').

Mostly, a fixed frequency ranging from 200 to 300 Hz has been chosen:

- 200 Hz [LKCS12]
- 220 Hz [MWW+15]
- 250 Hz [WWSK01, LMS12, NMAP+12, BCMS13, LWL+15]
- 280 Hz [KVW03]
- 300 Hz [JSA+10]

Only Ballardini et al. [BFC+20] used a frequency depending on the acceleration signal of L3. A higher acceleration goes along with a higher frequency.

Rantala and colleagues [RMK+17] recommended to take the sensitivity and preferences of the individual into account to ensure that feedback is perceived as pleasant.

In stochastic resonance stimulation (see section '2.2.6 Excursus: Stochastic Resonance Stimulation') vibration threshold, and consequently, the individual sensitivity is considered. However, in the research area of vibrotactile this seems to be rather uncommon. Even though it could be a promising approach, as it ensures that intensity is perceived equally in all subjects. The following excursus describes how the perception of stimuli works by the human skin.

2.3.3 Excursus: Mechanoreceptors of the Skin

The previous section showed locations and possible configurations of the vibrotactile stimuli. Obviously, for vibrotactile biofeedback it is of great importance to understand how the human receives the input. The human skin is composed of sensors which perceive mechanical, thermal and chemical signals of the environment or the body and transfer them to the central nervous system [BS18]. Five types of sensors can be distinguished in the skin [BS18, Joh02]:

- mechanoreceptor: responsive to skin deformation
- thermoreceptor: responsive to warming and cooling
- chemoreceptor: responsive to chemical stimuli
- nociceptor (free nerve endings): responsive to damaging or threatening stimuli
- itch receptor

Haptic perception is mainly dependent on mechanoreceptors, which can be further differentiated in the following receptors [BS18, Joh02] (Figure 2.6).

- Merkel: pressure sensors
- Ruffini: pressure sensors
- Meissner: touch sensors
- Pacinian: vibration sensors

An overview of the characteristics of the different receptors can be found in Table 2.2.

Pacinian receptors are extremely sensitive to vibrations, and consequently, they are in the main focus for vibrotactile biofeedback [Joh02]. They are fast-adapting and have low thresholds. The receptive area is big compared to the other receptors. Already single impulses can lead to conscious perception [BS18].

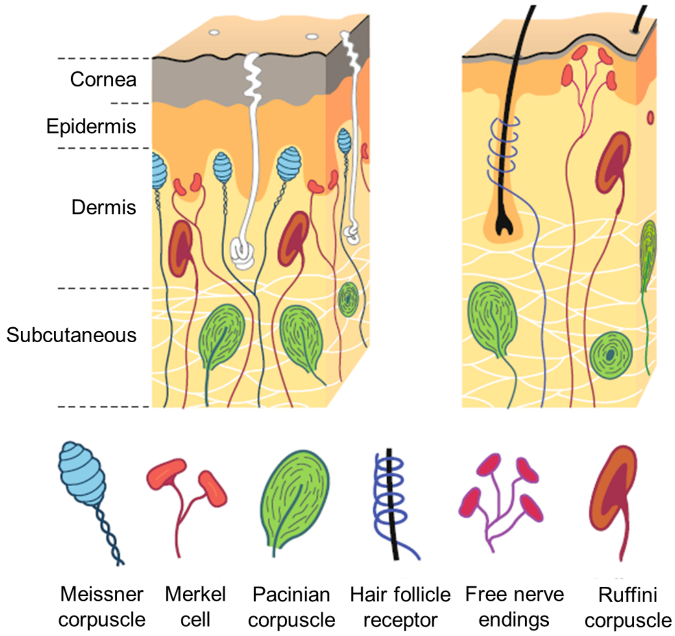

Figure 2.6: Mechanoreceptors in glabrous (left) and hairy (right) skin [BS18].

2.3.4 Determination of the Vibration Threshold

As previously shown, using an individual intensity of the vibrations might be promising. For this approach, the vibration threshold needs to be measured to be able to do so. Consequently, in this section, the term vibration threshold is introduced and three different methods for determining this value are presented. Finally, it is shortly explained, which factors can influence the vibration threshold.

According to Ghandi and colleagues [GSTB11] the vibration threshold can be defined as the smallest amplitude of vibration that can be sensed by the subject. Amongst others, vibration threshold testing is used for detecting peripheral neuropathies or investigating the carpal tunnel syndrome [GSTB11]. However, it can also contribute to standardizing the vibration intensity for vibrotactile feedback amongst individuals. According to the review of Ghandi et al. [GSTB11] the most common methods for determining the vibration threshold are Method of Limits (MOL), von-Békésy protocol and the Forced-Choice Method (FCM).

Different methods

Method of Limits (MOL)

In the MOL approach the intensity of the stimulus is steadily increased, e.g. from zero, until it is detected by the subject. Then, it is decreased, e.g. from a slightly supraliminal level, until is it no longer perceived [GSTB11, GL79]. Normally, a few test trials are executed to familiarize the subject with the procedure. For the deter-

Table 2.2: Mechanoreceptors of the skin and their properties [Joh02]

Afferent type	**SA1**	**RA**	**PC**	**SA2**
Receptor	Merkel	Meissner	Pacinian	Ruffini
Location	Tip of epidermal sweat ridges	Dermal papillae (close to skin surface)	Dermis and deeper tissues	Dermis
Sensory Function	Form and texture perception	Motion detection, grip control	Perception of distant event through transmitted vibrations, tool use	tangential force, hand shape, motion direction
Effective stimulus	Edges, points, corners, curvature	Skin motion	Vibration	Skin stretch
Frequency range	0-100 Hz	1-300 Hz	5-1000 Hz	0-? Hz
Peak sensitivity	5 Hz	50 Hz	200 Hz	0.5 Hz
Threshold	30 μm	6 μm	0.08 μm	300 μm
Spatial acuity	0.5 mm	3 mm	10+ mm	7+ mm

mination the procedure is usually repeated several times, e.g. three times, and the mean of the obtained values is referred to as the vibration threshold [GL79]. Stuart and colleagues [STS$^+$03] changed the steps approximately three times per second. The MOL is most commonly used to determine vibration thresholds [GSTB11].

Von-Békésy algorithm

This algorithm is a type of MOL. The stimulus is continuously applied with varying amplitudes [GSTB11, MG02]. It starts with a strong stimulus easy to perceive, which is then gradually decreased until the subject can no longer sense it. Consequently, the procedure continues with a slightly subthreshold amplitude until the signal becomes detected. This procedure is repeated until the threshold is isolated [GSTB11]. According to Morioka et al. [MG02] and Seah and colleagues [SG08] the algorithm can also be started with a stimulus increasing in intensity.

Forced-choice method (FCM)

In FCM two intervals are presented to the subject who has to identify in which interval the stimulus occurred [GSTB11, AJM90]. If the subject cannot identify a stimulus, s/he has to guess. The algorithm increases or decreases the intensity depending on whether the subject is correct or not. The amplitude is recognized if the subject identified the correct interval in at least three out of four comparisons [AJM90]. E.g. Mahns et al. [MPS+06] asked the subjects to indicate whether the stimulus has a higher frequency or the same as the standard stimulus.

Factors Influencing Vibration Threshold

The device, the testing procedure, and the characteristics of the subject can influence the vibration threshold [GSTB11, ZSSSK03]. These characteristics contain BMI, age, skin temperature, gender and diseases [GSTB11, GL79, Ver80, DSEB16]. However, there seems to be no significant differences over a day within one subject [LLN+15].

2.3.5 Sensing Unit

In the previous section mainly the design of the vibrotactile display was described. This chapter introduces different possibilities for designing the sensing unit. Obviously, the sensing unit of a vibrotactile feedback device plays an important role. Some studies use the forces measured under the feet by a force plate or pressure insoles [MWW+14], [MWW+15], whereas others base their threshold on body tilt measured by accelerometers and gyroscopes or an IMU [WWSK01], [ABOY15], [SBW12]. Those different devices are presented next.

Force Plate

Force plates are the gold standard for quantifying postural control due to their high accuracy [EYT17, JZB+16].

Basically two different technologies of force plates are available [PN15]. They can either be based on strain gages or piezoelectric sensors. Strain gages convert the mechanical strain into a change in electrical resistance, whereas in piezoelectric devices the crystals generate an electric charge in case of applied mechanical stress [Kle12]. Based on the derived moments and forces COP can be calculated [PN15]. Commonly used COP variables are amongst others the ellipse area, path length, velocity, SD and RMS. The velocity refers to the efficiency in postural control of the subject, with a smaller velocity indicating a better balance. It is a reliable measure among trials as well as the RMS [PN15].

Sampling frequencies of 50 Hz [JZB+16] or 100 Hz [KSL02, LMS12, SBW12] are typically used to assess standing balance.

Pressure Insoles/Force Sensors

Balance performance can also be assessed by plantar force sensors or pressure insoles [MWL+16]. They offer the advantage of not being limited to laboratory conditions [KLE+16], as they are wearable [MWL+16].

Koch and colleagues [KLE+16] investigated the reliability of the Medilogic® insoles (T&T medilogic Medizintechnik GmbH, Schönefeld, Germany), a commercially available system with a force plate, and found acceptable reliability for vertical ground

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reaction forces in most cases (e.g. standing).

Inertial Measurement Unit (IMU)
Another wearable solution to measure postural sway offer IMUs consisting of an accelerometer, a gyroscope and a magnetometer to measure acceleration, velocity and direction [MWL+16, GGP+19].
Some studies used e.g. only angular velocity sensors [NMAP+12], accelerometers [JSA+10] or accelerometer and gyroscope [WWSK01] to assess balance performance. However, an IMU offers the advantage of solving errors introduced by the gravity acceleration, as acceleration data are corrected by using a gyroscope/magnetometer system combined with a Kalman filter [VAMB+19].

Ghislieri et al. [GGP+19] showed in their review that in most cases wearable sensors, e.g. IMUs or accelerometers, are placed at the lower trunk near COM to assess balance. This finding is also supported by the literature concerning vibrotactile feedback. L1-3 [NMAP+12], L2-3 [KVW03], L2-4 [BCMS13], L3 [BFC+20, LMS12] have been recently used as reference position for biofeedback. Only Janssen and colleagues [JSA+10] and Wall and colleagues [WWSK01] placed the sensor at the head to avoid interference between the sensor and vibrotactile display. According to Ghislieri [GGP+19] the most frequently used position is at L5.
RMS of sway and mean sway velocity are among the most frequently used parameters derived from IMUs, as well as the range of acceleration, sway area or sway path length [GGP+19]. Commonly, measuring frequencies of 50 Hz [LKCS12, BFC+20] or 100 Hz [LMS12, SBW12, SBOW13, BCMS13] have been used to assess standing balance.

When designing a vibrotactile feedback device it is not only important to decide for an adequate sensing unit. But it also needs to be defined when the stimulations are applied. Consequently, the upcoming section focuses on reviewing the literature for different possibilities to set a threshold for feedback onset.

2.3.6 Setting the Threshold for Feedback Onset

For applying biofeedback there needs to be defined when and which motors are turned on. To get insights on how the threshold for feedback onset could look like, in the following it is described how this was done in recent literature in terms of parameters and formulas. Most studies use a dead area, in which no vibrations are applied (e.g. [BFC+20, BCK+18, BCMS13, LKCS12, MWW+15, NMAP+12]). Another option would be an always-on mode, where a motor linked to the direction of sway is vibrating [BFC+20]. However, this is not very common and is neglected in the following. For using a dead zone it is required to define a body sway threshold. As soon as this threshold is exceeded, the feedback is given until sway is again below the body sway threshold [BCMS13, LKCS12].

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Several authors just used a pre-set fixed body sway threshold for all their subjects of e.g. 0.5°, 1° or 1.5° of trunk tilt [AEPY18, BCMS13, FMF+13, FFG+13, KVW03, LKCS12, SBW12]. Goebel et al. [GSP+09] as well as Wall and colleagues [WWSK01] took 0.5° of head tilt for the body sway threshold.
However, literature shows that anthropometric measurements as height influence sway [ASM+12, AMS+15, CRC02]. Consequently, an individual body sway threshold for each subject seems beneficial to consider individual sway patterns.

Recently used formulas were based on the following parameters:

- angle [AEPY18, LKCS12, SBW12, WWSK01, ABOY15, AOCY16, FFG+13]
- velocity [NMAP+12]
- acceleration [BFC+20]
- plantar forces [ML17, MWW+15]

The following formulas have already been used to calculate an individual body sway threshold (t):

- based on the standard deviation SD of the acceleration signal during quiet standing [BFC+20]

$$t_1 = SD \tag{2.1}$$

- based on the range R of sway angular velocity during quiet standing with the extreme 5 % values of the histogram being excluded [NMAP+12]

$$t_2 = 40\ \% * 90\ \%\ R \tag{2.2}$$

- based on the mean $\bar{x}$ forces during quiet standing [MWW+15, ML17]

$$t_3 = 110\ \% * \bar{x} \tag{2.3}$$

$$t_4 = 120\ \% * \bar{x} \tag{2.4}$$

A further aspect which can be taken into account, when deciding for an adequate formula, is the percentage in time above threshold while using a certain formula. It is obvious that the feedback should not be turned on the whole time or, on the other hand, never turned on because of a too high body sway threshold. Consequently, if a formula produces such results e.g. in pre-testing, it might not be the best choice for the application.
In the study of Lee et al. [LKCS12] subjects were 40 % to 60 % of the time above threshold with feedback, whereas this was reduced to $<$ 20 % when using feedback. Bechly and colleagues [BCMS13] measured in subjects with peripheral vestibular

deficits 70 % without and 10 % with feedback as the percentage above threshold, whereas for healthy subjects values of 55 % were determined without feedback and 10 % with feedback.

Some authors, additionally, adapt the feedback depending on the amount of sway [KVW03, LWL$^+$15, WWSK01], whereas others just use the same motor with the same intensity for one direction (e.g. [LKCS12, JSA$^+$10]).
Lin et al. [LWL$^+$15] and Kentala and colleagues [KVW03] arrange two or three motors vertically above each other. Exceeding the first threshold leads to an activation of the bottom motors. In case sway becomes greater and a second threshold is exceeded, the vibration moves to the next row so that only one motor is active at the same time.
Wall and colleagues [WWSK01] use two different schemes. First, the pulse rate of the activated motor increases in case of increasing sway (interval-based coding). Second, more motors up the array are activated during increasing sway (position-based coding) [WWSK01].
Giving information about the severity of the deviation provides subjects with additional information about their sway.
Consequently, it seems to be important to use body sway thresholds adapted to the baseline sway of the subject and a formula, which is reasonable for the actual context (e.g. stance, eyes open/closed).

2.3.7 Trial Duration

The last aspect that needs to be considered for assessing the performance of the vibrotactile device is the trial duration. According to the systematic review of Ruhe et al. [RFW10] to reach acceptable reliability for COP parameters, the trial duration should not fall below 90 seconds. However, in the current literature of vibrotactile feedback, normally, a trial duration of 30 to 50 seconds has been used (Table 2.3). Consequently, a compromise needs to be found between reliability on the one hand, and fatigue on the other hand.

Table 2.3: Trial duration used in vibrotactile feedback studies.

Trial Duration	Paper
30 s	[AOCY16, AEPY18, WWSK01, BCK$^+$18, BCMS13]
40 s	[LKCS12]
45 s	[JSA$^+$10]
50 s	[BFC$^+$20]
90 s	[MWW$^+$14, MWW$^+$15]

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2.4 Human Postural Control

Human postural control is often modelled as an inverted pendulum. Mainly two strategies to control the inverted pendulum are described in the literature. The ankle strategy is rather used for short displacements, whereas in more perturbed situations the hip strategy is applied [HN86, Win95]. The used strategy also depends on the standing position. During narrow stance ankle strategy is applied in AP directions, whereas in ML directions a hip load/unload strategy is conducted by the hip abductors and adductors [Win95]. In other standing positions, like semitandem stance, both mechanisms work vice versa. In AP directions mainly hip strategy is applied and ML balance is controlled by an ankle mechanism of in the invertors and evertors [Win95, Mor20].
Several studies could demonstrate that more joints than just the ankle joint is involved in the process of quiet standing. Aramaki et al. [ANM+01] showed that movements at the ankle and hip joint are present during quiet standing. There is even a reciprocal correlation between the ankle and hip acceleration. Sasagawa et al. [SUKK09] also found a reciprocal relationship between ankle and hip joints in the sagittal plane. It was assumed that hip movements affect body kinematics during quiet standing. Hsu and colleagues [HSS+07] even investigated ankle, knee, hip, lumbosacral, cervical spine and atlanto-occipital joint. Their results suggested a control strategy which includes most major joints for postural control.
Recently, Federolf et al. [FRN13] suggested that an increased task difficulty (bipedal, tandem or one-leg stance) is associated with an increased complexity of the movements. This was concluded from a principal component decomposition where complex stances (tandem and one-leg stance) required more principal movement components to explain 90 % of the total variance.
In case subjects need to conduct a precision aiming task while standing quietly, Balasubramaniam et al. [BRT00] found that if the task was executed in parallel orientation, ML sway was reduced, whereas doing the aiming task in perpendicular orientation reduced AP sway. It was concluded that two independent postural subsystems, reciprocally connected, are evident in human postural control.
Additionally, the ankle muscle activation influences COP and Center of Gravity (COG) parameters [WWPL14]. High levels of activation led to increases in amplitude of COP and COG, whereas higher stiffness at the ankle joint decreased those parameters.
Also the respiratory mode (thoracic or abdominal) can influence posture. Recently, it was shown that thoracic breathing increased COP parameters (mean deviation) compared to abdominal breathing [HGL10].

Center of Pressure (COP) vs Center of Mass (COM)
COP and COM are two well-spread terms of postural control [Win95]. Those can be acquired by the different sensing units. The following paragraphs give a short definition of those measures and their interconnection.

The Center of Pressure (COP) is located at the vertical ground reaction force vector. All pressures which are in contact with the ground are considered. The weighted average of all these pressures represents the COP [Win95]. While standing with both feet on the ground the COP is situated somewhere between them. Its position reflects the neural control of ankle muscles [Win95, WPP+98].

The Center of Mass (COM) refers to the mass and position of the body segments. It is located in the global reference system at the point of the total body mass resulting from the weighted average of the COM of each body segment [Win95]. It should not be confused with the COG, which is the COM vertically projected to the ground.

As previously shown (see section '2.3.5 Sensing Unit'), the COP is usually determined via force plates, whereas estimations of COM movements can be drawn from IMU measurements [MWL+16]. Consequently, their interaction needs to be evaluated and considered.
During SOT conditions, which consists of quiet standing with eyes open/closed, acceleration measures of the pelvis showed a good correlation with COP [WRM+11]. Ekvall Hansson et al. [ET19] compared the outcomes of an IMU at L4 and a force plate. Very high and statistically significant correlations were found for eyes open and closed during standing.
Masani et al. [MVAN14] investigated the relationship between COP and COM during quiet standing. They found a higher correlation of COP velocity and COM acceleration compared to COP velocity and COM velocity [MVAN14]. Another finding suggested a proportional relationship between COP-COM and COM acceleration [GWFA04].
On the other hand, Seimetz and colleagues [STKL12] compared sway complexity from force plate and IMU at sternum level and suggested the existence of different control mechanism at COP and torso sway.
Additionally, cross-correlations of COM and COP following platform perturbations were either positive or negative depending on the subject suggesting different strategies for balance control, which might be caused by differences in neuromuscular activity [TGA+11].
Moreover, also vibrotactile feedback referenced to an IMU at L4 can lead to increases in COP, suggesting a type of perturbation induced by the vibrations [LWL+15]. However, there is limited research investigating the relationship between COP and COM while using vibrotactile feedback.

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Chapter 3

Research Questions and Hypotheses

The overall aim of this work is to provide a device which gives vibrotactile directional feedback to the upper torso based on body sway. Therefore, the effectiveness and intuitiveness of sway dependent vibrotactile directional feedback to the upper body on postural control are investigated. In a later application, it is thinkable to use the vest in everyday life to improve postural control, e.g. in the elderly or people with balance disorders.

The first major aim of this study is to identify the effectiveness of the sway dependent feedback. Recent literature has already shown that it is possible to improve postural control with vibrotactile feedback [BFC+20, LMS12, WWSK01] (see section '2.2.4 Vibrotactile Biofeedback'). Differing from other studies, we place the motors on the upper torso and use two motors to indicate the major directions (front, back, left and right), whereas for diagonal deviations only one motor is active.
Consequently, it will be tested if sway dependent vibrotactile directional feedback applied to the shoulder can improve postural control. Accordingly, the first hypothesis is:

> $\mathbf{H_0}$: Sway dependent vibrotactile directional feedback applied to the upper torso does not positively influence postural control (similar body sway μ).
>
> $$\mu_{\text{ Feedback}} \geq \mu_{\text{ No Feedback}}$$
>
> $\mathbf{H_1}$: Sway dependent vibrotactile directional feedback applied to the upper torso does positively influence postural control (lower body sway μ).
>
> $$\mu_{\text{ Feedback}} < \mu_{\text{ No Feedback}}$$

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The second major aim is to identify which type of instruction is more effective and intuitive for subjects - to move in the direction of vibrotactile feedback or move in the opposite direction. In section '2.3.1 Instructions and Direction', it was shown that there is no consensus, yet, which approach is more intuitive for subjects. It seems that moving in the direction of a stimulus is promising for biofeedback [ABOY15], but also to guide blind and visually impaired people [AMS14, BSG19]. On the other hand, moving in the opposite direction of the stimulus to null out the vibrations was studied for several times in the field of vibrotactile feedback for postural control [JSA+10, LKCS12, MWW+15] and can be understood in the sense of facing an obstacle which needs to be avoided. This leads to the second hypothesis:

> $\mathbf{H_0}$: The type of instruction (*attractive*, *repulsive* or *no instruction*) does not influence the effectiveness and intuitiveness on postural control (similar body sway μ).
>
> $$\mu_{\text{ Attractive}} = \mu_{\text{ Repulsive}} = \mu_{\text{ No instruction}}$$
>
> $\mathbf{H_1}$: The type of instruction (*attractive*, *repulsive* or *no instruction*) influences the effectiveness and intuitiveness on postural control (varying body sway μ).
>
> $$\mu_{\text{ Attractive}} \neq \mu_{\text{ Repulsive}} \neq \mu_{\text{ No instruction}}$$

Moreover, as a minor goal, it is investigated if feedback influences COP and the movements of an IMU near COM in the same manner. During normal quiet standing without receiving vibrotactile feedback, COP and COM tend to be correlated [WRM+11, ET19]. However, in case perturbations or vibrotactile feedback are applied, correlations and sway parameters derived of COP and of the lower torso by an IMU are differently influenced, indicating differences in control strategies [TGA+11, LWL+15]. This pattern is investigated by the third hypothesis:

> $\mathbf{H_0}$: Vibrotactile biofeedback does not influence the correlation between COP and L5 (near COM) derived data (similar correlation coefficent R).
>
> $$R_{\text{ Feedback}} = R_{\text{ No Feedback}}$$
>
> $\mathbf{H_1}$: Vibrotactile biofeedback influences the correlation between COP and L5 (near COM) derived data (varying correlation coefficent R).
>
> $$R_{\text{ Feedback}} \neq R_{\text{ No Feedback}}$$

Additionally, it is investigated if a learning effect exists over several trials when using feedback or not. Learning effects are rarely investigated in the field of vibrotactile biofeedback. It seems that no learning effect is evident when using real-time feedback [BCMS13, BFC+20]. However, a training period of eight weeks with feedback improved balance parameters [BCK+18]. Consequently, a period of several trials with feedback might increase the awareness of balance and enhance performance. Additionally, it is tested if several trials without feedback lead to an enhancement. Therefore, the fourth hypotheses is:

> $\mathbf{H_0}$: Seven trials of standing with and without feedback do not lead to a learning effect (similar body sway μ).
>
> $$\text{Feedback: } \mu_{\text{ trial1}} \leq \mu_{\text{ trial2}} \leq \ldots \leq \mu_{\text{ trial7}}$$
> $$\text{no Feedback: } \mu_{\text{ trial1}} \leq \mu_{\text{ trial2}} \leq \ldots \leq \mu_{\text{ trial7}}$$
>
> $\mathbf{H_1}$: Seven trials of standing with and without feedback do lead to a learning effect (decreasing body sway μ).
>
> $$\text{Feedback: } \mu_{\text{ trial 1}} > \mu_{\text{ trial 2}} > \ldots > \mu_{\text{ trial 7}}$$
> $$\text{no Feedback: } \mu_{\text{ trial 1}} > \mu_{\text{ trial 2}} > \ldots > \mu_{\text{ trial 7}}$$

Lastly, it is aimed to find out if subjects with higher baseline sway profit to a greater extent of the feedback compared to individuals with little baseline sway. Several studies related to biofeedback show that subjects with vestibular deficits profit to a greater extent from the cues compared to healthy controls [DCH05, DHC07, BCMS13, GBPP13]. Consequently, it is assumed that this pattern can also be replicated in healthy subjects with differences in baseline sway, leading to the fifth hypothesis:

> $\mathbf{H_0}$: There is no correlation R between baseline sway and the proportional reduction of sway due to biofeedback.
>
> $$R \leq 0$$
>
> $\mathbf{H_1}$: There is a positive correlation R between baseline sway and the proportional reduction of sway due to biofeedback.
>
> $$R > 0$$

All hypotheses are tested by analysing the outcomes of different sway parameters (RMS of sway and SD of velocity) derived from an IMU near COM (in the following named L5) and a force plate. Differences between these two reference devices can give insights in their effectiveness for determining and setting a body sway threshold depending on which feedback is given. For L5, additionally, the amount of changes and the percentage above threshold are calculated. Additionally, the subjective perception is captured and compared through a questionnaire.

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Chapter 4

Methods

In this section, the vest, the vibrotactile feedback, its configuration as well as the synchronization with an IMU and a force plate are described. Furthermore, the procedure and conclusions of our pilot study are presented. In the end, the set-up of the user study for the evaluation of the effectiveness and intuitiveness of the vest are depicted.

4.1 Vest

The device consists of four Eccentric Rotating Mass vibration motors (ERM; 10 mm vibration motor 310-122; Precision Microdrives Inc.). The characteristics of the DC motors can be found in Figure 4.1.

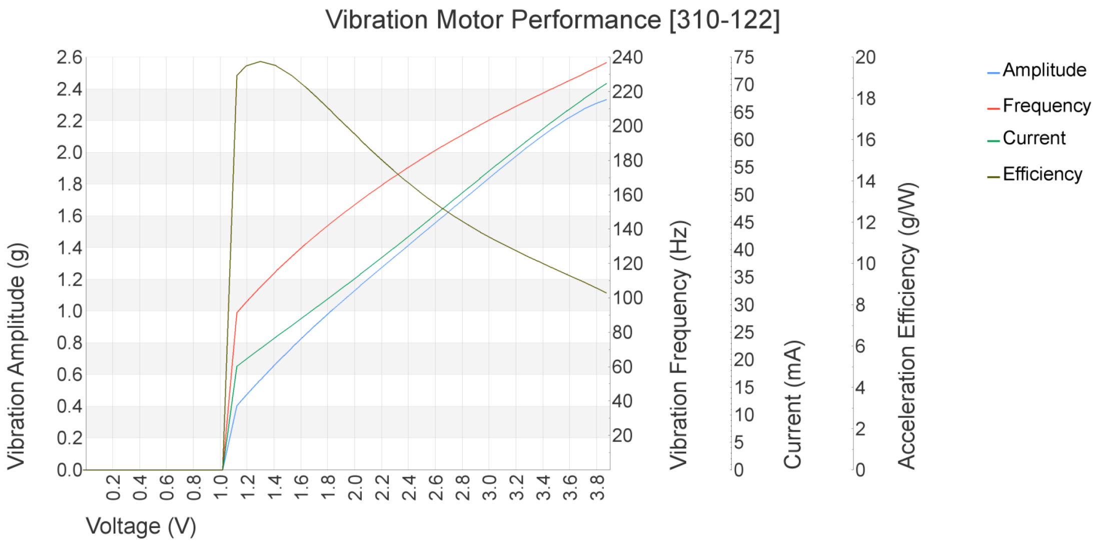
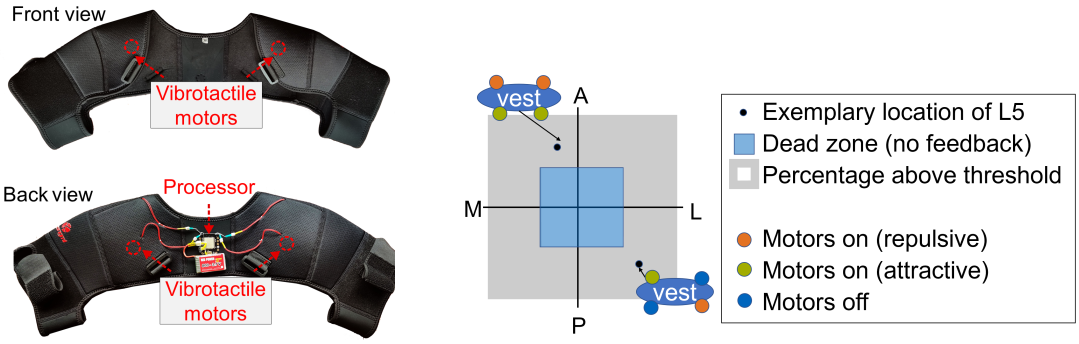


Figure 4.1: Motor performance characteristics [Pre20b].

The motors are connected to a Beetle-ESP32 Microcontroller (DFRobot) and powered by a 3.7 V-lithium polymer battery (Figure 4.2(a)). Pulse Width Modulation (PWM) is used to operate the motors. PWM is 'a pulse control in which the width or frequency of pulses is modulated within the period of the fundamental frequency so as to create a specific output voltage waveform' [RRCV15]. Only two states, 'on' and 'off', exist, whereby 'on' is the pulse width [Kum17]. The percentage of duty cycle, i.e. how long the voltage is 'on', and the status of all motors ('on' or 'off') are sent via Bluetooth Low Energy (BLE) to the microcontroller and its Arduino script to control the frequency and amplitude of the selected motors.



(a) (b)

Figure 4.2: a) Vest, fabric made with four ERM motors placed on the front and back side of the upper torso (front and back view); b) exemplary representation of motors on/off for attractive and repulsive feedback (Explanations: A = anterior, P = posterior, M = medial, L = lateral).

For the positioning of the front motors, the length of the clavicula was measured. They were attached beneath the clavicula at one-third of its length from the medial side. The back motors were placed in the gap between spina scapulae and margo medialis of the shoulder blade (Figure 4.3). Velcro was used to fix the motors on the vest, which was adjusted with straps to the subject to fit tightly. Two sizes of the vest were available (M, XL). The appropriate size was selected for each subject depending on body size.

4.1.1 Vibrotactile Feedback

Vibrotactile feedback was given based on body sway (Euler angles) according to an IMU placed near the COM at L5. Baseline trials at the beginning of the experiment were used to calculate an individual body sway threshold for each subject. If this threshold is exceeded in one or two directions, the vibrotactile feedback of the corresponding motor/s remained active as long as the angle was above the individual body sway threshold. As long as the subjects remained within the threshold, in the so-called 'dead zone', no feedback is provided. The raw signal of the IMU is used for vibrotactile feedback. The exact procedure for calculating the body sway threshold is described in section '4.5.1 Procedure'.

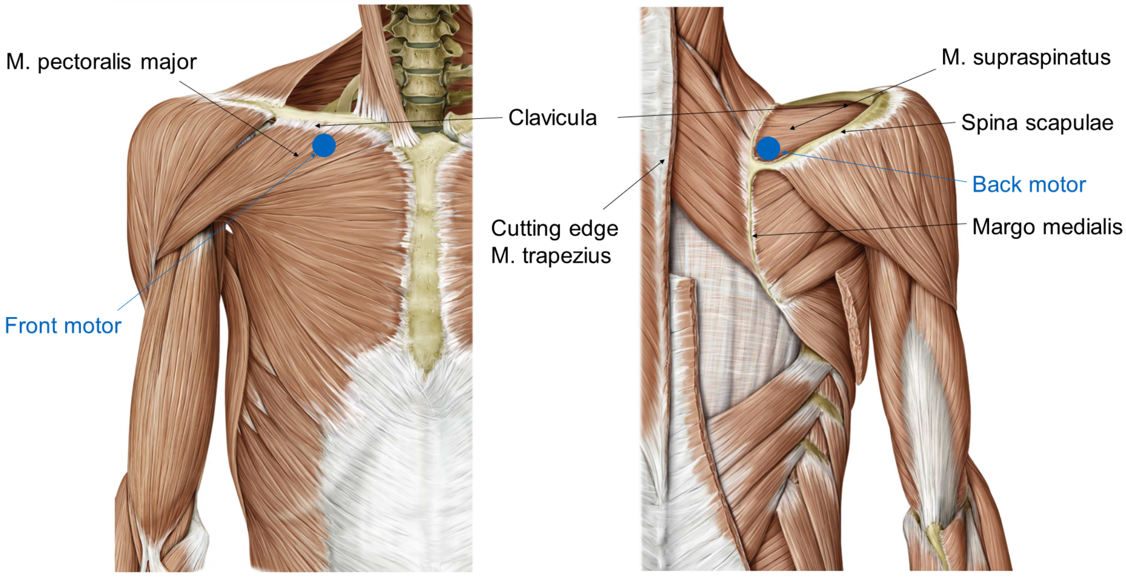


Figure 4.3: Position of the motors (based on [SSS+18]).

Two different coding schemes existed, the *attractive* and the *repulsive* mode. In the *attractive* mode, the motor opposite to the direction of sway vibrated. E.g. if the subject swayed in the anterior direction, the back motors were activated. In case the body sway threshold was exceeded in two directions (e.g. posterior and right) only one motor vibrated (front-left motor) (Figure 4.2(b)). For the *repulsive* mode the coding was vice versa. Motors in the direction of sway were activated. E.g. if the subject swayed to the front, the front motors were turned on. Again, if two body sway thresholds were exceeded simultaneously, only one motor was vibrating (e.g. subject swayed in the posterior direction and to the right, then, the right-back motor was activated) (Figure 4.2(b)).

Technically, this was implemented through a MQ Telemetry Transport (MQTT) protocol. This is a messaging protocol consisting of a broker-based publish-subscribe mechanism. It is well suited for applications where nearly real-time exchange between several devices is required [Hil17].
In our case, MQTT.fx (Deters, Erlangen, Germany) was used as broker or server. All the clients were connected to this broker. The publisher, which was the client sending messages, was a C++ script. This script received and saved the data of the IMU and the force plate. Additionally, Euler angles of the IMU were processed to determine if motors needed to be activated or deactivated. In case a status change was required, the script sent a message to the broker containing the status of all four motors (e.g. "1100" indicated that both front motors are on) as well as the motor intensity of

the front and back motors. The broker received the message and forwarded it to the subscriber. In our case, this was a python script which sent the status change via BLE to the vest. Figure 4.4 gives an overview of the communication processes and data flow.

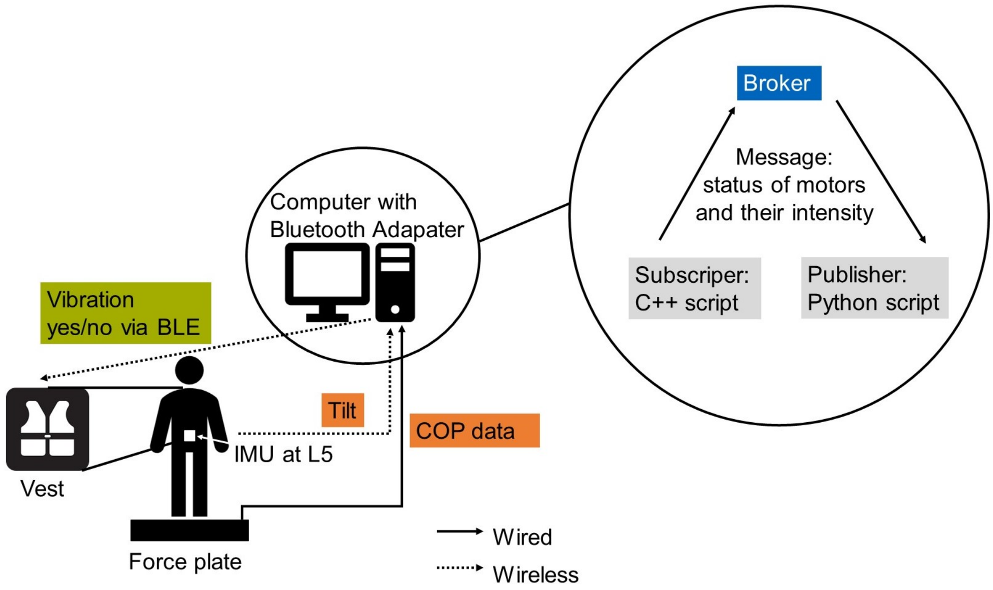


Figure 4.4: Communication between the different devices.

4.1.2 Intensity Standardization of Vibrotactile Feedback

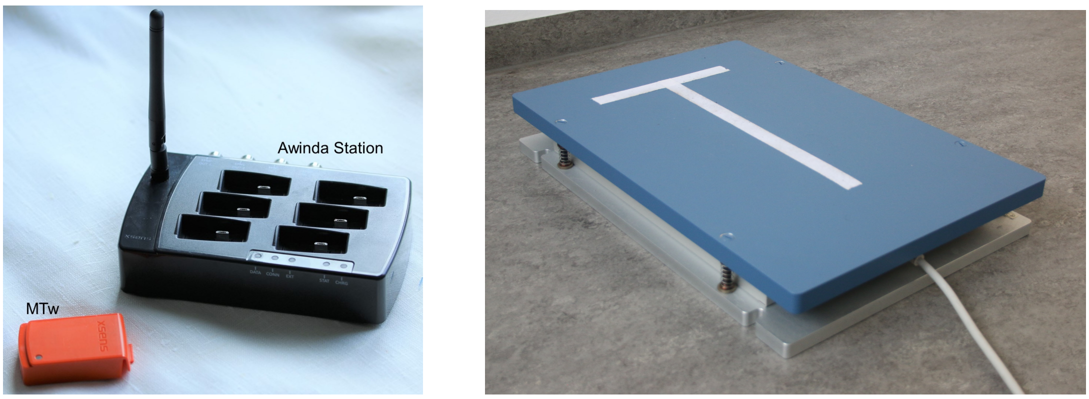
To standardize the vibration intensity, the vibration threshold was determined for each subject individually. This procedure ensured that all subjects perceived vibrations with a similar intensity.
Subjects stood with their feet hip-wide apart, the arms alongside their body and eyes open. The procedure is based on the MOL approach. The intensity of the stimulus was increased from zero three times per second by 1 % until the subject pressed a button to indicate that the stimulus was noticed. This stopped the stimulus. Then, the stimulus decreased from 80 % of the maximum motor intensity until the subject pressed the button again to indicate that the stimulus was no longer perceivable. The range of 0 % to 80 % was chosen, as it was indicated by pretests that the vibration threshold is in the middle of this range at around 40 %. This procedure was repeated for three times and the mean of the six obtained values was used as the vibration threshold. One practice trial was always conducted in the beginning to familiarize the subjects with the procedure. In section '4.4.2 Results and Conclusions' it is shown how we specified the intensity for the different motors.

4.2 Measurement Devices

To quantify sway movements at L5 were measured through an IMU. A force plate was used additionally to determine COP parameters.

4.2.1 IMU

One MTw Awinda Wireless 3DOF Motion Tracker (Xsens, Enschede, Netherlands) with the Awinda Master was used to capture Euler angles as well as velocity data near COM with a sampling frequency of 100 Hz (Figure 4.5(a)). Therefore, the IMU was placed at L5. L5 is the vertebra below the connecting line between the highest points of the left and right crista iliaca [SSS+18]. Motors were far enough away to ensure that there was no interference caused by the motors.
Before the IMU was attached with double-sided tape directly to the skin of the subject, a filter warm-up of 30 seconds without moving it was executed as recommended by the manufacturer [PSRB18]. Before each trial and as soon as the subject was standing quietly, an alignment reset was conducted to set the orientation to zero. The Mtw sensor sent the data wirelessly to the Master, which was connected via USB to a computer. Data acquisition was done with the MT Software Development Kit (SDK) by the C++ script.



(a) (b)

Figure 4.5: a) XSens MTw and the Awinda Master; b) AMTI force plate.

4.2.2 Force Plate

An AMTI force plate (Advanced Mechanical Technology, Inc., Watertown, MA), strain gage based, was used to be able to calculate COP trajectories (Figure 4.5(b)). The sampling frequency was set to 100 Hz. The force plate was zeroed before each trial in an unloaded state. The AMTI USB Device SDK was used via the C++ script to save and synchronize the data with the IMU.

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4.3 Stances

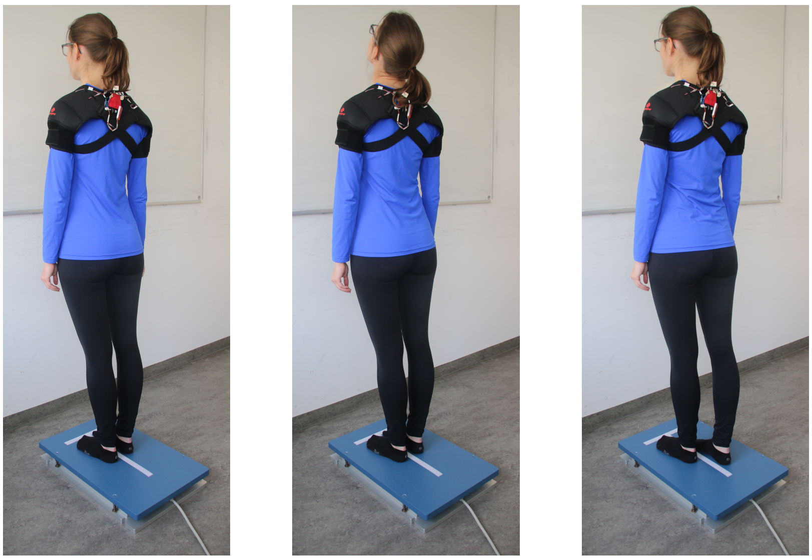
The following stances were used during the pilot and the user study. During the trials subjects were instructed to always stand quietly with closed eyes and arms hanging on their sides. They should not touch the body (Figure 4.6).

Quiet Standing: This posture required standing with the feet parallel and 2.5 cm apart and looking straight forward. The position of the subject was marked on the force plate (Figure 4.6(a)). It was used to calculate the body sway threshold depending on which feedback was applied.

Narrow Stance: Subjects stood with their feet parallel and 2.5 cm apart. They were instructed to position their head in the neck (Figure 4.6(b)).

Semitandem Stance: The toes of the dominant foot were aligned with the middle of the non-dominant foot. Footedness was determined by the foot which kicks a stationary ball. Feet were parallel and 2.5 cm apart and subjects looked straight forward. Subjects were instructed to distribute their weight equally between legs (Figure 4.6(c)).

Narrow stance and semitandem stance were used to test the effectiveness of the vest.



(a) (b) (c)

Figure 4.6: Different stances: a) quiet standing, b) narrow stance with head in the neck and c) semitandem stance.

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4.4 Pilot Study

We conducted a pilot study to 1) identify differences in vibration threshold between the front and back of the upper torso and accordingly determine a pleasant intensity of the vibrations, 2) choose an adequate trial duration and 3) select a formula for the calculation of the body sway threshold for the user study.

4.4.1 Procedure

After a short introduction about the procedure, participants signed the informed consent. Due to the pandemic situation they needed to confirm with their signature that they were symptomless of Covid-19 and had had no contact with a diseased person over the last 14 days. Exclusion criteria were assessed with a questionnaire and body height and weight were measured. Then, the vest and the IMU were attached as previously described (see section '4.1 Vest' and '4.2.1 IMU'). A motor check was conducted to verify that the vibrations of all motors could be easily perceived. In the next step the vibration threshold was determined for all four motors separately (regarding the procedure see section '4.1.2 Intensity Standardization of Vibrotactile Feedback'). The order of the motors was randomized. Consequently, the reference motor, which was the motor with the highest vibration threshold, was determined and used as the reference for the subjective perception. Figure 4.7 gives an overview over the procedure.

Subjective Perception

All eight motor combinations, which were relevant for the user study, were tested: front-left (FL), front-right (FR), back-left (BL), back-right (BR), front (FL & FR), back (BL & BR), left (FL & BL) and right (FR & BR). These were presented in a randomized order at 110 %/120 %/130 % of vibration threshold of the reference motor and at maximum motor intensity. Consequently, 32 combinations were applied. Each combination consisted of three stimuli with a duration of 250 ms and a one second break in-between followed by a stimulus of one second. Afterwards, subjects rated the pleasantness of the stimulus on a 7-point Likert scale from 1 (very inconvenient) to 7 (very convenient). In case two motors were active, they had to state additionally if they were perceived equally in strength or if one was stronger, stating the stronger one, although the motors vibrated with the same intensity.

The pilot study continued with several trials in the different stance positions to obtain sway data. No vibrotactile feedback was provided during these trials. The trial duration was set to 90 seconds. First, three quiet standing trials were conducted, followed by five narrow stance and five semitandem stance trials, which appeared block-randomized.

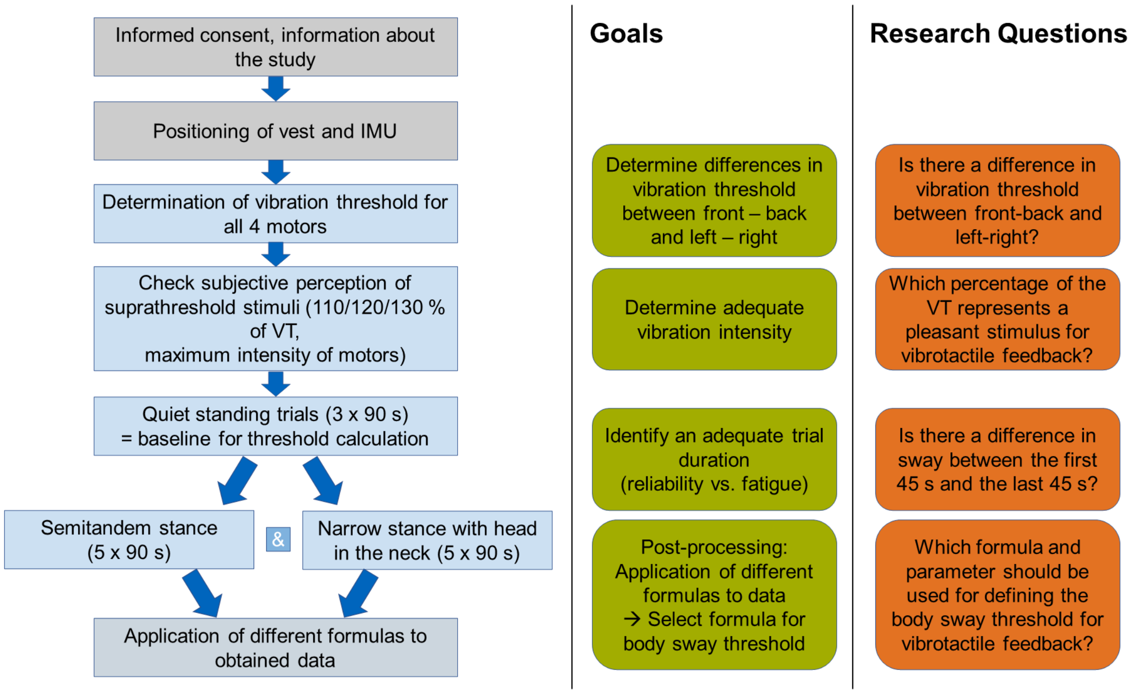


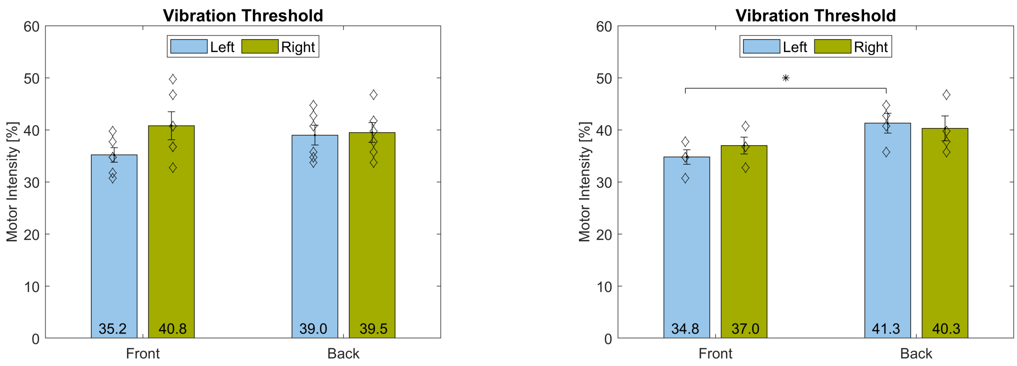
Figure 4.7: Procedure, goals, and research questions of the pilot study.

4.4.2 Results and Conclusions

Six subjects, 3 female and 3 male, with a mean age of 25.2 ± 1.0 years and an average BMI of 21.5 ± 2.5 kg/m^2 participated.

Differences in Vibration Threshold between Front - Back and Left - Right
When considering all subjects, no significant differences were evident for the vibration threshold as indicated by a repeated measures ANOVA (Front-Back: $F(1,5) = 0.28$, $p = .622$, ${\eta_p}^2 = .052$; Left-Right: $F(1,5) = 3.51$, $p = .120$, ${\eta_p}^2 = .413$) (Figure 4.8(a)). However, two subjects showed high values for the FR-motor compared to the other subjects. They perceived the vibration late. For one of the subjects a repetition of the measurement a few days later led to a threshold comparable to the other subjects (39 instead of 50). Probably, the positioning of the motor was the reason for this discrepancy. Consequently, in such cases the positioning of the motors should be verified and the vibration threshold determination should be repeated during the user study. For further investigation of the vibration thresholds these two subjects were excluded.
A repeated measures ANOVA for the remaining four subjects showed a significant difference between front and back ($F(1,3) = 24.40$, $p = .016$, ${\eta_p}^2 = .891$), whereas no differences occurred between left and right ($F(1,3) = 0.57$, $p = .504$, ${\eta_p}^2 = .160$). Bonferroni post hoc tests indicated a significant difference between the FL and BL

motor (p = .034), only. For the right side no significant difference was obvious (p = .248) (Figure 4.8(b)).

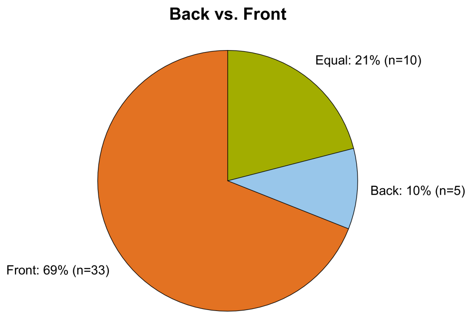


(a) (b)

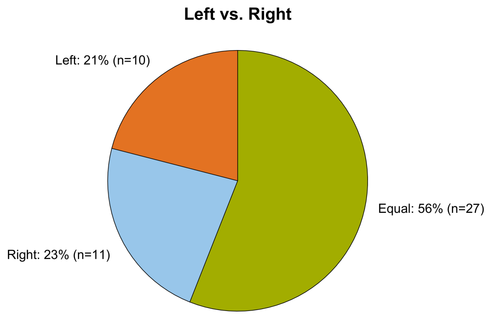
Figure 4.8: Vibration threshold for all four motors a) (n = 6) and b) (n = 4); error bars represent the standard error of the mean; statistical significance indicated by $^{*}p < .05$.

For further investigation of the differences in vibration threshold the amount of namings for the stronger motor during the subjective perception was considered. When comparing left (FL vs BL) and right (FR vs BR) side for the front and back motors, it was obvious that in most of the cases (33 out of 48) the front motor was perceived to be stronger (Figure 4.9(a)). In some cases, participants felt them equally strong (10 out of 48), whereas the back motor was only named five times. When comparing the front (FL vs FR) and the back (BL vs BR) side for the left and right motors, the pattern was less consistent. However, in more than half of the comparisons, motors were perceived to be equal in strength (27 out of 48) (Figure 4.9(b)). For the remaining comparisons either the motors of the left (10 out of 48) or right side (11 out of 48) seemed to be stronger. This pattern was not consistent over the subjects, some have always perceived the motors of one side stronger, whereas for other subjects it was diverse, whether they felt the left or the right motors more intense.

Consequently, it was assumed that differences in perception between left and right were a matter of positioning. Through motor checks in the beginning of the user study it is ensured that the intensity of both motors is sensed the same. However, the data showed differences in vibration threshold between front and back of the upper torso and therefore supported the results of Kim et al. [KK17].
For the user study it was concluded that a different intensity for front and back motors based on vibration threshold is adequate and needs to be implemented.



(a)



(b)

Figure 4.9: Amount of namings for the stronger motor a) back vs front and b) left vs right; n = 48.

Adequate Vibration Intensity

Looking at the overall ratings of the different motor intensities during the subjective perception, revealed that higher intensities tended to be more pleasant for the participants (Figure 4.10). However, when considering the single motors and the motor combinations, a huge variability became obvious (Figure 4.11). Additionally, the ratings given by one subject were not consistent, e.g. once 120 % of vibration threshold was rated very high, whereas in another combination the maximum intensity of the motors was preferred. Additionally, while observing the subjects, some cringed at maximum intensity and reported that the intensity is too strong. These facts contradicted using the maximum intensity. Furthermore, taking just the maximum intensity would make it impossible to use a different intensity for front and back motors, and consequently, the stimulus would not be individualized anymore.

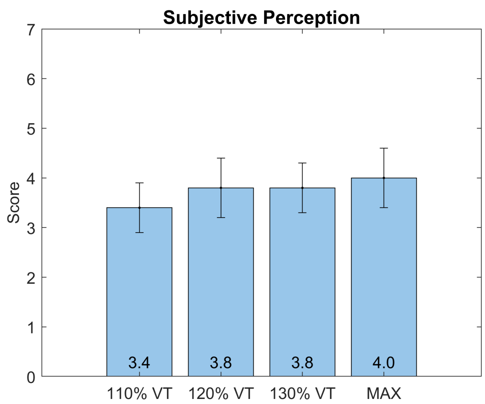
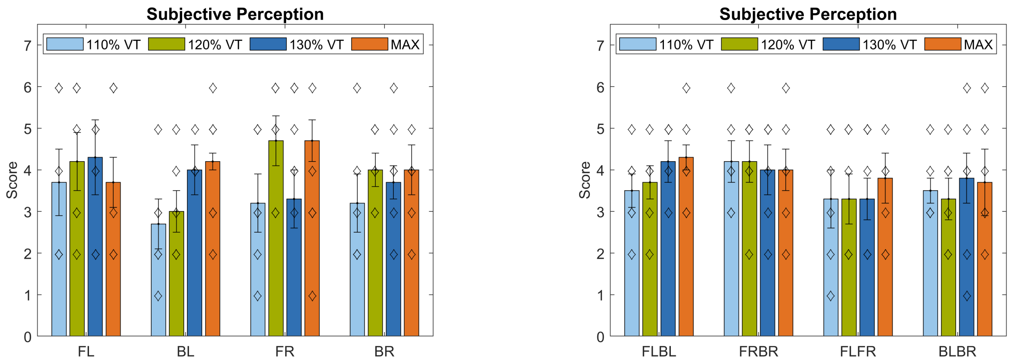


Figure 4.10: Rating of subjective perception of all motors and combinations according to intensities; error bars represent the standard error of the mean; n = 6.



(a) (b)

Figure 4.11: Rating of subjective perception ordered according to a) motors and b) motor combinations; VT = vibration threshold; error bars represent the standard error of the mean; diamonds represent each subject; n = 6.

Therefore, and based on the measured vibration thresholds it was suggested for the user study to determine the vibration threshold for both motors on the back and take the mean of both values as reference. For the back motors 130 % of the obtained value is set as intensity, whereas 120 % is used for the front motors.

Adequate Trial Duration

The RMS of sway is a commonly used performance indicator for balance [AEPY18, LKCS12, SBOW13]. Therefore, this parameter was calculated for three periods (1-90 s, 1-45 s, 46-90 s) to identify if performance decreased over time.

In ML directions no significant differences were found. In AP directions the ANOVA was significant for all three stances (quiet standing, narrow stance and semitandem stance). Bonferroni post hoc tests showed significant differences between seconds 1-45 vs 1-90 (p = .043) and 1-45 vs 46-90 (p = .049) for narrow stance (Figure 4.12). This pattern, however not significant, was also visible in the two other stance conditions and indicated a loss in performance over time (Figures in the appendix A.1). Additionally, some subjects reported their arms falling asleep and holding the head in the neck for such a long time as inconvenient.

Consequently, a trial duration of 45 seconds is used in the user study. Further analysis of the IMU data in the following also only refers to the first 45 seconds.

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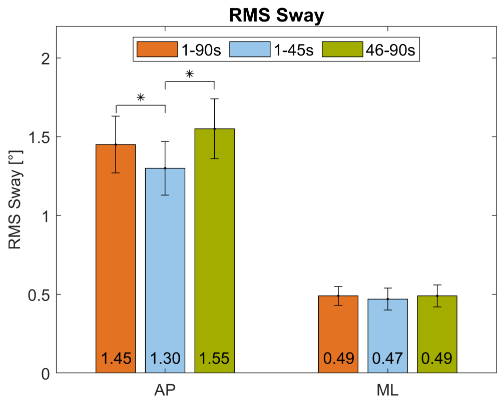

Figure 4.12: RMS of sway for narrow stance; error bars represent the standard error of the mean; statistical significance indicated by *p < .05; n = 6.

Formula for Applying Feedback

As previously described, several formulas have been used to calculate a body sway threshold for applying vibrotactile feedback (see section '2.3.6 Setting the Threshold for Feedback Onset').

We used these formulas to calculate the body sway thresholds using acceleration as well as tilt data based on the quiet standing trials:

- based on the standard deviation SD

$$t_1 = SD \tag{4.1}$$

- based on the range R with the extreme 5 % values of the histogram being excluded

$$t_2 = 40\ \% * 90\ \% R \tag{4.2}$$

- based on the mean $\bar{x}$

$$t_3 = 110\ \% * \bar{x} \tag{4.3}$$

$$t_4 = 120\ \% * \bar{x} \tag{4.4}$$

These formulas were applied to the acceleration and tilt data of narrow stance and semitandem stance. For determining a suitable formula the percentage above threshold was considered during quiet standing without receiving feedback, which should be approximately around 50 % as well as the amount of changes between 'on' and 'off' of the feedback.

First, the formulas for the acceleration data were investigated. Figure 4.13 shows the results for the formula based on the SD for narrow stance. The percentage above

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threshold was roughly in the desired range. However, a huge amount of changes was present. Every second there would have been around 18 changes in AP directions and 15 changes in ML directions. This pattern was also observed for the other formulas as well as for semitandem stance when using acceleration data.

The corresponding feedback, consisting of steadily switching between 'on' and 'off', would probably be hard to understand for individuals. Furthermore, it cannot be guaranteed that non-vibrating motors correspond with standing upright, as e.g. standing bent forward calmly would result in non-vibrating motors. Consequently, calculating the formula based on acceleration data was not further investigated.

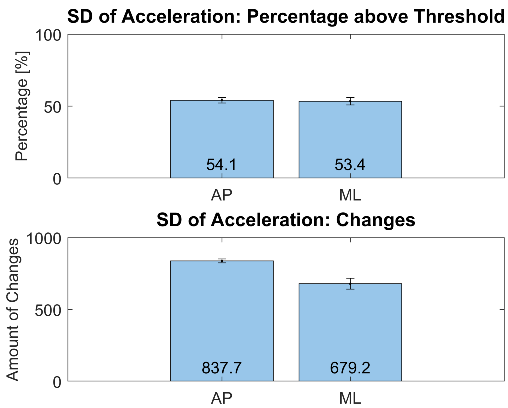
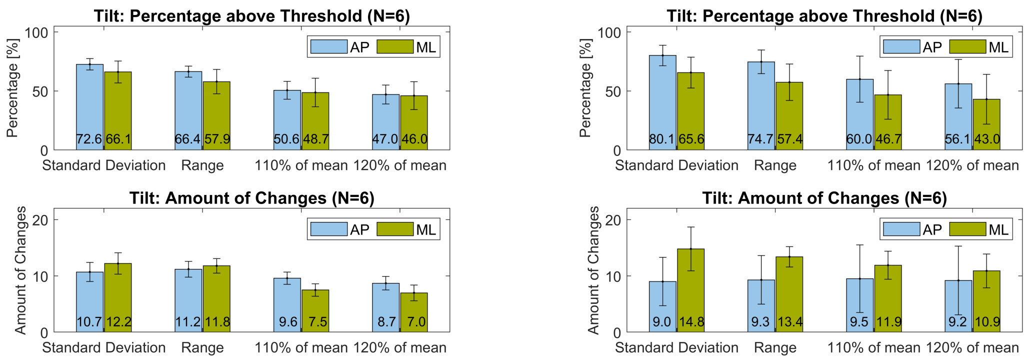


Figure 4.13: Percentage above threshold and amount of changes for narrow stance based on the standard deviation of acceleration data; error bars represent the standard error of the mean; n = 6.

Second, the results for the formulas based on tilt data were compared for both stances (Figure 4.14(a) for narrow stance and Figure 4.14(b) for semitandem stance). The amount of changes for the tilt values was decreased and seemed to be more reasonable for vibrotactile feedback. However, it was evident that, especially for semitandem stance and in AP directions, the formulas consisting of SD as well as of range provoked a too high percentage above threshold compared to the values from earlier research and cannot be considered to be adequate for the user study.

Nevertheless, the formulas consisting of the mean seemed to be promising in terms of the percentage above threshold as well as of the amount of changes. As the standard error is quite high, it was decided to take the formula '120 % of mean' instead of '110 % of mean' to calculate the body sway threshold for providing vibrotactile feedback in the user study. A further advantage of this formula is that it can be used for both stances (narrow stance and semitandem stance), which would also be valuable for later application.



(a) (b)

Figure 4.14: Percentage above threshold and amount of changes for a) narrow stance and b) semitandem stance for the different formulas based on tilt; error bars represent the standard error of the mean; n = 6.

4.5 User Study

To investigate the effectiveness of the vest on human postural control, we conducted a cross-sectional experimental study. Furthermore, we compared the intuitiveness of three different types of feedback.

4.5.1 Procedure

First, participants were shortly introduced into the study. After signing the informed consent (see appendix A.3 Material for the User Study), the rules according to the pandemic situation were explained and the participant confirmed being symptomless of Covid-19 and without contact to a diseased person over the last 14 days. We used a questionnaire to determine if any of the exclusion criteria were met (see section '4.5.2 Inclusion and Exclusion Criteria').
Afterwards, body height and weight were measured and the vest and the IMU were attached as previously described (see 'section 4.1 Vest' and '4.2.1 IMU'). The perception of the vibrations of the four motors was tested. In case a motor or combination (front or back side) was too weak or too strong, we adjusted the positioning. As soon as the subjects perceived all motors well, the vibration threshold was determined for both back motors (see section '4.1.2 Intensity Standardization of Vibrotactile Feedback'). The mean of both values was taken as reference for the intensity of the front (120 %) and the back (130 %) motors. Again the perception of the motors was tested. This time, additionally, the left (FL and BL) and right (FR and FL) motors were tested together. In case one motor was dominant, the weaker one was adjusted up to 5 % of motor intensity so that they were perceived equally strong. The procedure is visualized in Figure 4.15.

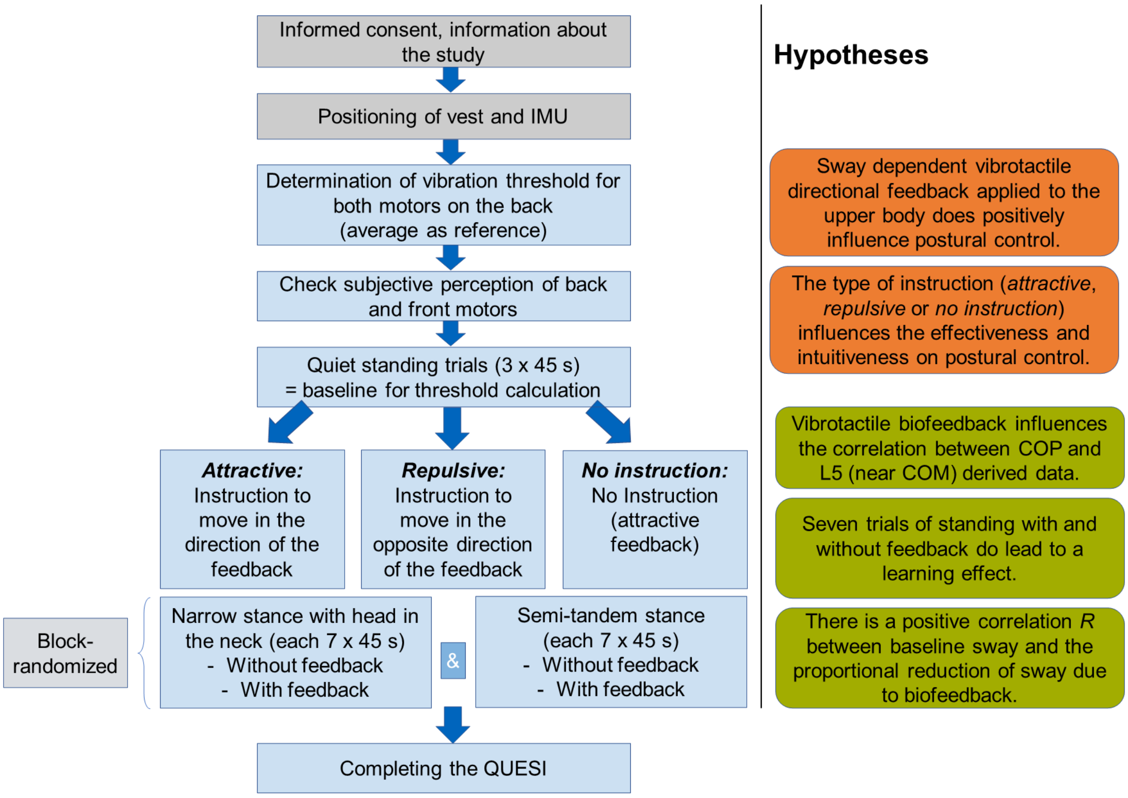


Figure 4.15: Procedure of the user study

In the next step, three quiet standing trials were conducted to measure baseline sway. A MATLAB script (The MathWorks, Natick, MA) calculated the body sway thresholds for the vibrotactile feedback in AP and ML directions ($1.2 * mean_{\text{L5 tilt angle}}$) based on the IMU data of the three trials. Force plate data were measured additionally.

Subjects were randomly assigned to one of three equal-sized groups:

- *Attractive*: Instruction to move in the direction of vibrotactile feedback (feedback indicated the direction, in which movement was required) (n=10)
- *Repulsive*: Instruction to move in the opposite direction of vibrotactile feedback (feedback indicated the direction, where the subject had to move away from) (n=10)
- *No instruction*: no instruction was given about the direction of vibrotactile feedback; feedback was given in an attractive way (n=10)

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Then, we tested four conditions:

- narrow stance without feedback
- narrow stance with feedback
- semitandem stance without feedback
- semitandem stance with feedback

All subjects received the instruction that the vest gives vibrotactile feedback in some trials, which informs about their sway, and eventually further instructions according to their group affiliation.
The order of the conditions was block-randomized across subjects. Each order appeared once in each group to avoid order effects. However, to allow cooling of the processor of the vest, it was avoided that both feedback conditions appeared directly one after each other.
The trial duration was set to 45 seconds. We conducted seven trials for each of the four conditions to consider intra-personal variability. 30 seconds of rest were provided between trials. In case subjects needed more time to recover further rest was given.
In the end, subjects were asked to complete the Questionnaire for Measuring the Subjective Consequences of Intuitive Use (QUESI) to obtain subjective feedback about the vibrotactile feedback (see appendix A.3 Material for the User Study).
The study execution followed the guidelines of the declaration of Helsinki and was approved by the Clinical Research Ethics committee of the Medical School of the Technical University of Munich.

4.5.2 Inclusion and Exclusion Criteria

Subjects needed to be aged between 18 and 35 years and have a BMI of less than 30 kg/m^2 to ensure a well-fitting of the available vests. They wore socks and a tight shirt. Not being able to stand with closed eyes for 45 seconds led to exclusion from participation. Furthermore, participation was rejected if neurological, orthopaedic or rheumatic diseases were known which could negatively affect standing with closed eyes. Any pain while standing or difficulties while following the instructions of the investigator led to exclusion of the study.

4.5.3 Data Analysis

Data handling
Data post-processing was performed using a MATLAB routine. The first and last 2.5 seconds were cut from each trial so that 40 seconds were analysed of the force plate as well as the IMU data. A mean value was calculated for all conditions and parameters from trial two to seven for each subject. To identify possible learning effects, all seven trials per condition were considered.

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Filtering
Force plate data were filtered with a zero-phase second-order Butterworth low-pass filter with a cut-off frequency of 10 Hz. IMU data were already filtered by the integrated Kalman filter [PSRB18].

Parameters
RMS of body sway as well as the SD of velocity were calculated for COP and L5 data. For L5, additionally the amount of changes between 'on' and 'off' of the feedback and the percentage above threshold were determined.

Statistical Analysis
For the different sway parameters a mixed model Analysis of Variance (ANOVA) was calculated to identify the main effects of group and feedback as well as interaction effects. Bonferroni post hoc tests were used to identify statistically significant differences between conditions and groups. To further investigate the data a univariate ANOVA with Bonferroni post hoc tests was calculated to check for significant differences between the three groups (*repulsive*, *attractive* and *no instruction*) for the different conditions (feedback and no feedback for narrow stance and feedback and no feedback for semitandem stance). To investigate differences between feedback and no feedback in the different groups, dependent t-tests were used for both stance conditions.

The 14 items (5-point scale Likert type) of QUESI were assigned to the five subscales: *Subjective Mental Workload*, *Perceived Achievement of Goals*, *Perceived Effort of Learning*, *Familiarity* and *Perceived Error Rate*. The mean value of the corresponding items revealed the score for the subitem. The *QUESI score* is the mean value over all items. High values go along with a higher probability of intuitive use. E.g. the maximum value of the subscale *Perceived Error Rate* means that few errors occurred and the system was working without errors. For the different subitems and the *QUESI score* a univariate ANOVA was calculated across the different groups.

To see if normal distribution was given for the different variables, the Shapiro-Wilk test was calculated and QQ-plots were visually inspected. Levene test was used to test for homogeneity. However, according to Bortz et al. [BW05], analysis of variance is robust against violations of assumptions in case of equal-sized samples and groups of more than nine subjects, which was the case here.

A Pearson correlation was calculated between COP and L5 data for feedback and no feedback. According to Cohen, the correlation can be either small ($0.1 < |r| < 0.3$), moderate ($0.3 < |r| < 0.5$) or strong ($|r| > 0.5$) [BW05].

To compare sway parameters for the seven different trials in the different groups, another mixed model ANOVA was calculated for feedback and no feedback separately.

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Here, the repeated measures factor had more than two factors. Consequently, sphericity was considered by Mauchly-test. If sphericity was not given, degrees of freedom were corrected. In case Greenhouse-Geisser-Epsilon is $< .75$ Greenhouse-Geisser-Correction (GG.) was used, otherwise Huynh-Feldt-Correction (HF.) was applied ($\epsilon > .75$) [Gir03].
In case of a significant interaction effect a univariate ANOVA was calculated to investigate the simple main effects of group. Additionally, a repeated measures ANOVA was used to determine the simple main effects of trial.

A further Pearson correlation was calculated to find out if subjects with low body sway during quiet standing profit less of feedback and vice versa. Therefore, the proportional reduction was calculated and correlated with the results of the baseline trials:

$$ProportionalReduction = \frac{noFeedback - Feedback}{noFeedback} \tag{4.5}$$

Consequently, a positive correlation means that subjects with high baseline sway profit more of the feedback compared to subjects with low baseline sway.

${\eta_{\mathrm{p}}}^2$ was calculated as effect size for all analysis of variance, whereas for t-tests, Cohen's d ($\mathrm{d_z}$) was used. For all statistical tests, the significance level was set to .05.

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Chapter 5

Results

In this chapter, first, the subjects and their characteristics are shown. Then, sway parameters are presented for L5 and COP in terms of availability of feedback and type of instruction (*attractive*, *repulsive* and *no instruction*). Additionally, the outcomes of the QUESI are displayed. A correlation is calculated between sway parameters measured at L5 and COP. Moreover, it is examined, whether a learning effect occurs over the seven trials with feedback and without. The last section of this chapter investigates the relationship between sway parameters during baseline trials and the proportional reduction due to feedback.

5.1 Subjects

All 30 subjects fulfilled the inclusion criteria and participated in the study (Table 5.1). To ensure that subjects in the different groups were comparable in terms of their general characteristics an univariate ANOVA was computed. No significant differences between groups were visible for age, gender, BMI and waist girth.

Vibration Thresholds and Motor Intensities

A mixed model ANOVA was calculated to determine differences in vibration thresholds between groups and between the left and right side of the back. Neither the interaction (F(2,27) = 0.52, p = .603, $\eta_p{}^2$ = .037), nor the main effect of motor (F(1,27) = 0.07, p = .792, $\eta_p{}^2$ = .003) or group (F(2,27) = 2.15, p = .136, $\eta_p{}^2$ = .137) were significant. Consequently, vibration thresholds were similar between groups, which underlines their comparability (Figure 5.1). Furthermore, the findings of the pilot study that there are no differences in sensitivity between left and right side if motors are placed precisely were confirmed.

A univariate ANOVA was used to investigate whether the final motor intensities which were determined for the front (120 % of vibration threshold) and back side (130 % of vibration threshold) based on the vibration threshold differed amongst groups. For the front side as well as for the back side no significant differences were

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found (Table 5.1). Consequently, groups are comparable in terms of motor intensities. Motor intensity of the front corresponded to ~97 ± 7.7 Hz, whereas the back side vibrated at ~105 ± 9.2 Hz.

Table 5.1: Subject characteristics, motor intensities, and thresholds for vibrotactile feedback (mean ± standard deviation).

	Overall (N = 30)	**Group Att** (N = 10)	**Group Rep** (N = 10)	**Group nI** (N = 10)	**p**
Age [y]	25.9 ± 2.9	25.5 ± 3.4	24.7 ± 2.1	27.5 ± 2.4	.075
Gender [% male]	50%	50%	50%	50%	-
BMI [kg/m²]	23.1 ± 2.5	22.6 ± 3.0	23.5 ± 2.8	23.2 ± 1.6	.694
Waist [cm]	75.8 ± 5.7	75.4 ± 7.3	76.6 ± 4.7	75.3 ± 5.2	.859
Motor Intensity (front) [%]	46.7 ± 3.8	48.5 ± 4.0	45.1 ± 3.8	46.5 ± 3.0	.127
Motor Intensity (back) [%]	50.4 ± 4.4	52.4 ± 4.4	48.5 ± 4.4	50.4 ± 3.9	.139
Threshold AP [°]	1.5 ± 1.0	1.8 ± 1.3	1.3 ± 0.6	1.4 ± 1.0	.524
Threshold ML [°]	0.6 ± 0.3	0.5 ± 0.3	0.5 ± 0.2	0.7 ± 0.5	.457

Explanations: Att = attractive group; Rep = repulsive group; nI = no instruction group.

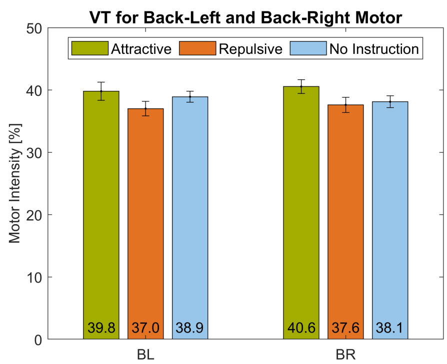

Figure 5.1: Vibration threshold for back-left (BL) and back-right (BR) motor for the different groups; error bars represent the standard error of the mean; n = 30.

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Body Sway Thresholds for Vibrotactile Feedback

At the beginning of the experiment, three quiet standing trials were performed to determine the body sway threshold upon which feedback was given to the subject. Thresholds were based on IMU data and the mean sway angle in ML and AP directions over the three trials. Again, groups were compared in terms of their performance. A univariate ANOVA revealed no significant differences between groups in ML and AP directions (Table 5.1). Accordingly, the three different groups were comparable concerning their baseline sway.

5.2 Influences of Feedback and Group

To investigate the influence of feedback and the type of instruction on postural control, a mixed model ANOVA was calculated for the different parameters (RMS of displacement in ML and AP, SD of velocity in ML and AP), both stances (narrow stance, semitandem stance) and L5 and COP, respectively. For L5 the amount of changes between 'on' and 'off' of feedback and the percentage above threshold were determined, additionally. Furthermore, using an univariate ANOVA, the three types of instruction were compared for both stances with and without feedback. To compare feedback vs no feedback, t-tests were calculated for each group separately. For the ANOVA and the t-tests significant results and tendencies are presented in this chapter. Additional non-significant results can be found in the tables in the appendix (A.2 Results of the Statistical Tests).

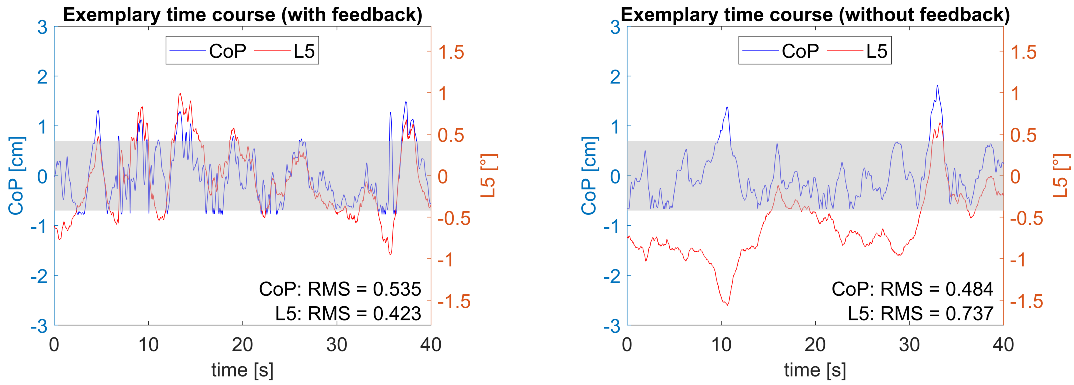
5.2.1 L5

In the following, the results of RMS of body sway, SD of velocity, amount of changes, and percentage above threshold are presented for L5. This analysis aimed to contribute to the first two major hypotheses, which investigated 1) the influence of the feedback applied by the vest and 2) the influence of the three different instruction groups. Figure 5.2 shows exemplarily the time course of the L5 trajectory for feedback and no feedback.

RMS of Sway

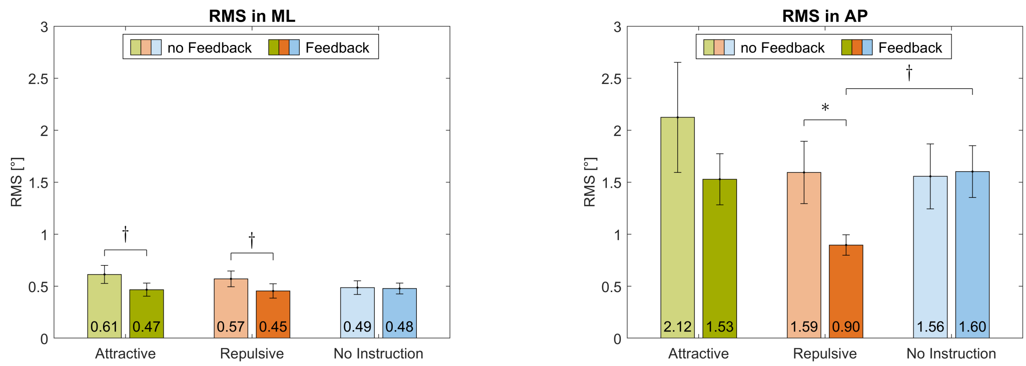
<u>Narrow Stance</u>

In narrow stance feedback significantly reduced the RMS in ML directions ($F(1,27) = 6.23$, $p = .019$, ${\eta_p}^2 = .188$) compared to no feedback. There was no interaction ($F(2,27) = 1.33$, $p = .282$, ${\eta_p}^2 = .090$) and main effect of group ($F(2,27) = 0.22$, $p = .806$, ${\eta_p}^2 = .016$) (Table A.1).
T-tests showed tendencies that with feedback the RMS in the *attractive* ($t(9) = -1.84$, $p = .099$, $d_z = .581$) and *repulsive* ($t(9) = -1.98$, $p = .079$, $d_z = .626$) group was smaller compared to with no feedback (Figure 5.3(a) and Table A.3).



(a) (b)

Figure 5.2: Exemplary time course of the L5 and COP trajectory a) with and b) without feedback; grey area represents the dead zone; white areas represent the percentage above threshold for L5.



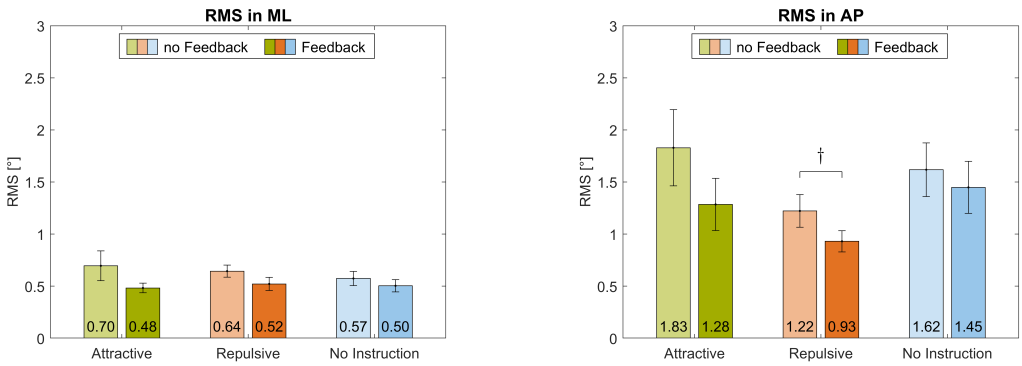
(a) (b)

Figure 5.3: RMS of L5 in a) ML and b) AP directions for narrow stance; error bars represent the standard error of the mean; statistical significance indicated by $^{\dagger}p < .1$, $^{*}p < .05$; n = 30.

In AP directions the same pattern occurred. There was a significant main effect for feedback ($F(1,27) = 7.44$, $p = .011$, $\eta_p{}^2 = .216$), which indicates that RMS of sway was lower in case feedback was available. The interaction between feedback and group ($F(2,27) = 2.33$, $p = .116$, $\eta_p{}^2 = .147$) and the main effect of group ($F(2,27) = 1.03$, $p = 371$, $\eta_p{}^2 = .071$) were not significant (Table A.1).
T-tests showed that the RMS was significantly reduced with feedback in the *repulsive* group ($t(9) = -2.78$, $p = .021$, $d_z = .879$) compared to no feedback (Figure 5.3(b) and Table A.3).

In ML directions no differences occurred between the three different groups. However, in AP directions the ANOVA for feedback was significant (F(2,27) = 3.42, p = .047, $\eta_p{}^2$ = .202). Bonferroni post hoc tests showed a tendency towards a higher RMS in the *no instruction* group compared to the *repulsive* group (p = .074) (Figure 5.3(b) and Table A.2).

<u>Semitandem Stance</u>
No interaction between feedback and group (F(2,27) = 0.66, p = .523, $\eta_p{}^2$ = .047) and no main effect of group (F(2,27) = 0.17, p = .843, $\eta_p{}^2$ = .013) were found for RMS of L5 in ML directions of semitandem stance. However, feedback led to a significantly smaller RMS (F(1,27) = 6.92, p = .014, $\eta_p{}^2$ = .204) (Table A.1).
T-tests to compare feedback and no feedback were not significant in all groups (Figure 5.4(a) and Table A.3).



(a) (b)

Figure 5.4: RMS of L5 in a) ML and b) AP directions for semitandem stance; error bars represent the standard error of the mean; statistical significance indicated by †p < .1; n = 30.

This pattern also appeared in AP directions. There was no interaction (F(2,27) = 0.63, p = .540, $\eta_p{}^2$ = .045) and no main effect of group (F(2,27) = 1.61, p = .218, $\eta_p{}^2$ = .107), but the main effect of feedback was significant (F(1,27) = 5.83, p = .023, $\eta_p{}^2$ = .178), indicating an decreased RMS of sway with feedback compared to no feedback (Table A.1).
For the *repulsive* group there was a tendency towards a smaller RMS when feedback was available compared to no feedback (t(9) = -2.25, p = .051, d_z = .710) (Figure 5.4(b) and Table A.3).

No significant differences occurred between groups for feedback and no feedback in ML and AP directions (Table A.2).

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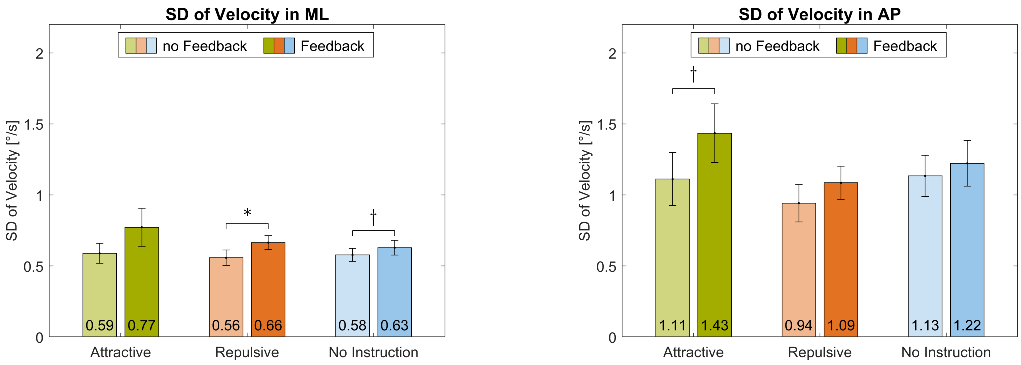
SD of Velocity

Narrow Stance

Now the results for the SD of velocity are presented. In ML directions no significant interaction effect of feedback and group (F(2,27) = 0.71, p = 510, $\eta_p{}^2 = .050$) and no significant main effect of group (F(2,27) = 0.46, p = .638, $\eta_p{}^2 = .033$) were found for narrow stance. However, the main effect of feedback was significant (F(1,27) = 6.19, p = .019, $\eta_p{}^2 = .186$) (Table A.1). Accordingly, there was a higher SD of velocity in ML directions with feedback.

In the *repulsive* group (t(9) = 2.68, p = .025, $d_z = .849$) the SD of velocity was significantly higher with feedback compared to no feedback, and in the *no instruction* group existed a tendency towards this pattern (t(9) = 1.94, p = .084, $d_z = .614$) (Figure 5.5(a) and Table A.3).



(a) (b)

Figure 5.5: Standard deviation of velocity of L5 in a) ML and b) AP directions for narrow stance; error bars represent the standard error of the mean; statistical significance indicated by $^{\dagger}p < .1$, $^{*}p < .05$; n = 30.

In AP directions the same pattern was obvious. The interaction (F(2,27) = 1.26, p = .299, $\eta_p{}^2 = .243$) and the main effect of group (F(2,27) = 0.75, p = .480, $\eta_p{}^2 = .053$) were not significant. Feedback, however, had a significant main effect (F(1,27) = 8.66, p = .007, $\eta_p{}^2 = .243$) (Table A.1). Consequently, the SD of velocity was higher when feedback was available.

In the *attractive* group a tendency towards a higher SD of velocity with feedback existed (t(9) = 2.01, p = .076, $d_z = .635$) compared to no feedback (Figure 5.5(b) and Table A.3).

Between the three groups no significant differences occurred for feedback and no feedback in ML and AP directions (Table A.2).

Semitandem Stance

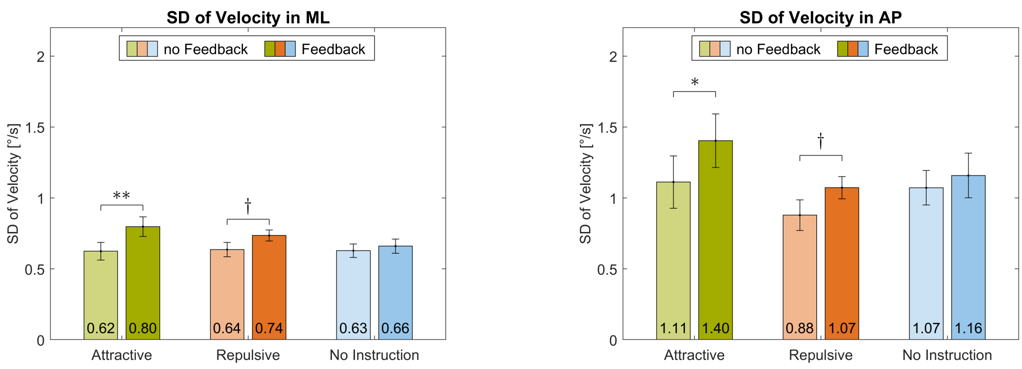
In semitandem stance the interaction between feedback and group ($F(2,27) = 2.53$, $p = .099$, ${\eta_p}^2 = .158$) and the main effect of group ($F(2,27) = 0.47$, $p = .630$, ${\eta_p}^2 = .034$) were not significant in ML directions for the SD of velocity. However, there was a significant main effect of feedback ($F(1,27) = 15.81$, $p = .001$, ${\eta_p}^2 = .366$) (Table A.1). Again, feedback led to an increased SD of velocity.

In the *attractive* group feedback led to a significantly higher SD of velocity ($t(9) = 3.33$, $p = .009$, $d_z = 1.048$), and in the *repulsive* group a tendency towards this pattern existed ($t(9) = 2.05$, $p = .071$, $d_z = .649$) compared to no feedback (Figure 5.6(a) and Table A.3).

In AP directions the same pattern was observed. No significant interaction ($F(2,27) = 1.24$, $p = .305$, ${\eta_p}^2 = .084$) and no main effect of group ($F(2,27) = 1.04$, $p = .366$, ${\eta_p}^2 = .072$) were obvious. A significant main effect of feedback ($F(1,27) = 12.91$, $p = .001$, ${\eta_p}^2 = .323$) occurred indicating a higher SD of velocity with feedback (Table A.1).

In the *attractive* group the SD of velocity was significantly higher with feedback compared to no feedback ($t(9) = 2.75$, $p = .023$, $d_z = .869$), and in the *repulsive* group a tendency towards this pattern existed ($t(9) = 2.25$, $p = .051$, $d_z = .711$) (Figure 5.6(b) and Table A.3).

No significant differences were found for the three different groups in ML and AP directions by the ANOVA (Table A.2).



(a) (b)

Figure 5.6: Standard deviation of velocity of L5 in a) ML and b) AP directions for semitandem stance; error bars represent the standard error of the mean; statistical significance indicated by $^{\dagger}p < .1$, $^{*}p < .05$, $^{**}p < .01$; $n = 30$.

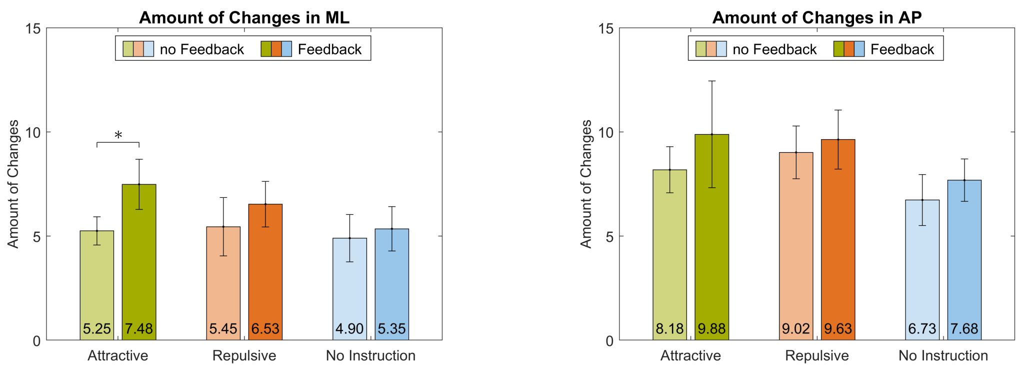
Amount of Changes

Narrow Stance

When looking at the amount of changes between 'on' and 'off' of the feedback during narrow stance in ML directions there was a non-significant interaction between feedback and group ($F(2,27) = 0.85$, $p = .437$, ${\eta_p}^2 = .060$). Feedback ($F(1,27) = 4.94$, $p = .035$, ${\eta_p}^2 = .155$) showed a significant main effect, whereas the main effect of group was not significant ($F(2,27) = 0.40$, $p = .672$, ${\eta_p}^2 = .029$) (Table A.1). This indicates that with feedback more changes occurred compared to no feedback.
The t-tests showed that the *attractive* group had significantly more changes with feedback compared to no feedback ($t(9) = 2.46$, $p = .036$, $d_z = .\text{-}779$) (Figure 5.7(a) and Table A.3).

In AP directions neither the interaction effect ($F(2,27) = 0.11$, $p = .896$, ${\eta_p}^2 = .008$), nor the feedback ($F(1,27) = 1.28$, $p = .269$, ${\eta_p}^2 = .045$) or group ($F(2,27) = 0.81$, $p = .456$, ${\eta_p}^2 = .056$) main effect were significant (Figure 5.7(b) and Table A.1). Consequently, the additional t-tests were also not significant (Table A.3).

The ANOVA over the different groups was neither significant for feedback nor for no feedback in ML and AP directions (Table A.2).



(a) (b)

Figure 5.7: Amount of changes of L5 in a) ML and b) AP directions for narrow stance; error bars represent the standard error of the mean; statistical significance indicated by $^*p < .05$; $n = 30$.

Semitandem Stance

In semitandem stance again the interaction effect for the amount of changes was not significant ($F(2,27) = 0.69$, $p = .511$, ${\eta_p}^2 = .049$) in ML directions. The main effects of feedback (F)1,27) = 2.67, $p = .114$, ${\eta_p}^2 = .090$) and group ($F(2,27) = 0.38$, $p = .686$, ${\eta_p}^2 = .028$) were not significant neither (Table A.1).

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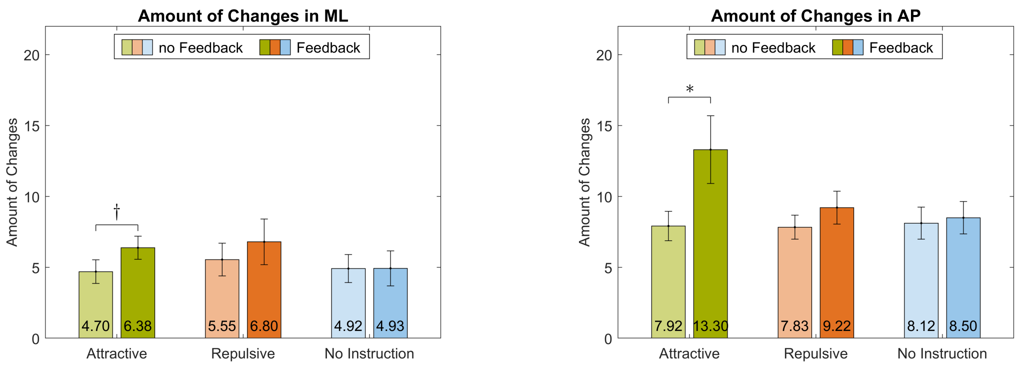
T-tests indicated that feedback compared to no feedback had the tendency to lead to more changes in the *attractive* group (t(9) = 2.08, p = .068, d_z = .657) (Figure 5.8(a) and Table A.3).

In AP directions there was a significant interaction effect (F(2,27)= 3.91, p = .032, ${\eta_p}^2$ = .225) as well as a main effect of feedback (F(1,27) = 9.53, p = .005, ${\eta_p}^2$ = .261). More changes were observed with feedback compared to no feedback. The main effect of group (F(2,27) = 1.11, p = .344, ${\eta_p}^2$ = .076) was not significant (Table A.1). In the *attractive* group there were significantly more changes with feedback (t(9) = 3.02, p = .014, ${\eta_p}^2$ = .957) compared to no feedback (Figure 5.8(b) and Table A.3).

The additional ANOVAs to compare the different instruction groups were not significant for feedback and no feedback in ML and AP directions (Table A.2).



(a) (b)

Figure 5.8: Amount of changes of L5 in a) ML and b) AP directions for semitandem stance; Error bars represent the standard error of the mean; statistical significance indicated by †p < .1, *p < .05; n = 30.

Percentage above Threshold

<u>Narrow Stance</u>

Additionally, the percentage above threshold, which is the proportion of receiving feedback, was investigated. In ML directions a significant interaction between feedback and group (F(2,27) = 4.45, p = .021, ${\eta_p}^2$ = .248) as well as a significant main effect of feedback (F(1,27) = 17.55, p < .001, ${\eta_p}^2$ = .394) were found for the percentage above threshold, whereas the main effect of group was not significant (F(2,27) = 0.39, p = .684, ${\eta_p}^2$ = .028) (Table A.1). Consequently, in the feedback condition a lower percentage above threshold was observed meaning that subjects remained longer in the dead zone.
To investigate the simple main effects of the between-subject factor group a univariate ANOVA was calculated. However, no differences between groups were found for

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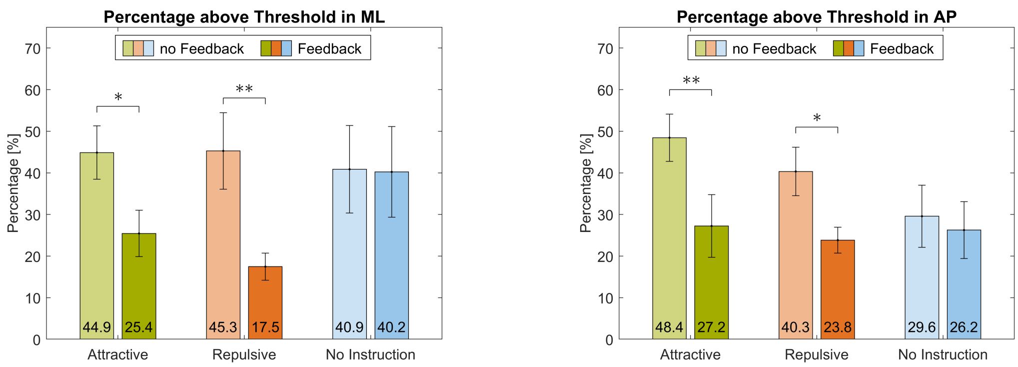
feedback ($F(2,27) = 2.50$, $p = .101$, $\eta_p{}^2 = .156$) and no feedback ($F(2,27) = 0.08$, $p = .928$, $\eta_p{}^2 = .006$) (Table A.2).
Additionally, the simple main effects of the within-subject factor feedback were considered. Consequently, t-tests were calculated for the different groups separately. In the *attractive* ($t(9) = -2.76$, $p = .022$, $d_z = .870$) and *repulsive* ($t(9) = -3.53$, $p = .006$, $d_z = 1.116$) group the availability of feedback led to significant decreases in the percentage above threshold compared to no feedback, whereas this was not observed for the *no instruction* group ($t(9) = -0.15$, $p = .887$, $d_z = .044$) (Figure 5.9(a) and Table A.3).

In AP directions the interaction effect ($F(2,27) = 3.19$, $p = .057$, $\eta_p{}^2 = .191$) for the percentage above threshold nearly met the conventional level of significance. The main effect of feedback was significant ($F(1,27) = 20.84$, $p < .001$, $\eta_p{}^2 = .436$) indicating a lower percentage above threshold with feedback. The main effect of group ($F(2,27) = 0.77$, $p = .475$, $\eta_p{}^2 = .054$) was not significant (Table A.1).
Additional ANOVAs confirmed the absence of differences between the three groups (Table A.2).
In the *attractive* ($t(9) = -3.42$, $p = .008$, $d_z = 1.082$) and *repulsive* ($t(9) = -3.07$, $p = .013$, $d_z = .971$) group the percentage above threshold was significantly higher without feedback compared to feedback. In the *no instruction* group feedback had no influence on this parameter ($t(9) = -0.91$, $p = .388$, $d_z = .284$) (Figure 5.9(b) and Table A.3).



(a) (b)

Figure 5.9: Percentage above threshold of L5 in a) ML and b) AP directions for narrow stance; error bars represent the standard error of the mean; statistical significance indicated by *$p < .05$, **$p < .01$; $n = 30$.

<u>Semitandem Stance</u>
The ANOVA for the percentage above threshold in ML directions of semitandem stance revealed no significant interaction ($F(2,27) = 2.18$, $p = .132$, $\eta_p{}^2 = .139$), whereas a significant main effect of feedback ($F(1,27) = 18.70$, $p < .001$, $\eta_p{}^2 = .409$)

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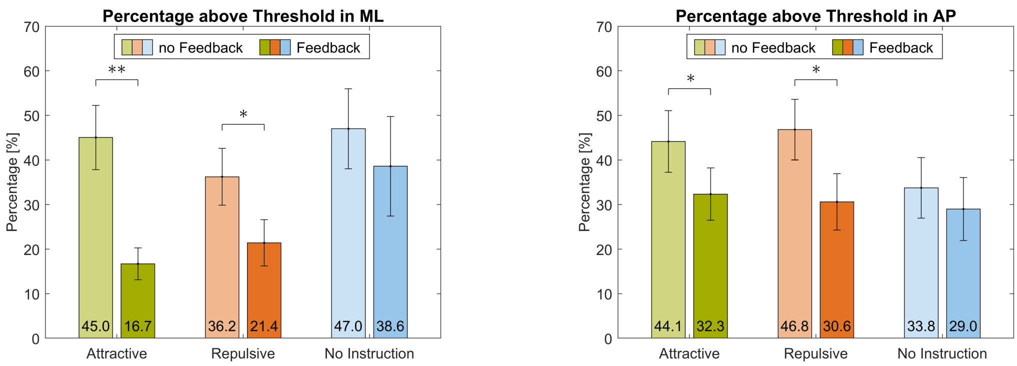
occurred. Consequently, with feedback a smaller percentage above threshold was observed. The main effect of group was not significant ($F(2,27) = 1.28$, $p = .293$, ${\eta_p}^2 = .087$) (Table A.1).
In the *attractive* ($t(9) = -4.19$, $p = .002$, $d_z = 1.322$) and the *repulsive* ($t(9) = -3.11$, $p = .013$, $d_z = .980$) group feedback led to a smaller percentage above threshold compared to no feedback. This was not evident in the *no instruction* group ($t(9) = -0.98$, $p = .353$, $d_z = .310$) (Figure 5.10(a) and Table A.3).

In AP directions the interaction effect was not significant ($F(2,27) = 1.40$, $p = .265$, ${\eta_p}^2 = .094$), whereas feedback showed a significant main effect ($F(1,27) = 15.01$, $p = .001$, ${\eta_p}^2 = .357$). Consequently, the percentage above threshold was lower when feedback was available compared to no feedback. The main effect of group was non-significant ($F(2,27) = 0.44$, $p = .647$, ${\eta_p}^2 = .032$) (Table A.1).
In the *attractive* ($t(9) = -3.15$, $p = .012$, $d_z = .992$) and the *repulsive* ($t(9) = -2.68$, $p = .025$, $d_z = .844$) group the percentage above threshold was reduced when feedback was available compared to no feedback. Again, for the *no instruction* group no differences were found ($t(9) = -1.05$, $p = .323$, $d_z = .333$) (Figure 5.10(b) and Table A.3).

No significant differences were obvious for the three different groups by the ANOVA in ML and AP directions (Table A.2).



(a) (b)

Figure 5.10: Percentage above threshold of L5 in a) ML and b) AP directions for semitandem stance; error bars represent the standard error of the mean; statistical significance indicated by *$p < .05$, **$p < .01$; $n = 30$.

Overall, for L5 a decreased RMS of sway, an increased SD of velocity as well as a decreased percentage above threshold were found when comparing feedback and no feedback. Additionally, in some cases a higher amount of changes was observed with feedback compared to no feedback. Differences between feedback and no feedback were mostly visible for the *attractive* and *repulsive* group. In the next section, the results for COP are presented.

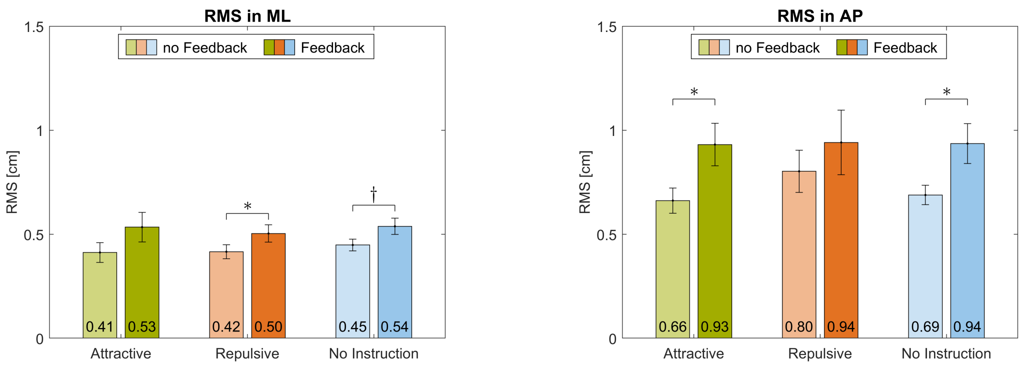
5.2.2 COP

In the following, the results of RMS of sway and SD of velocity for COP are shown, which also contribute to the first and second hypotheses. Figure 5.2 shows exemplarily the time course of the COP trajectory for feedback and no feedback.

RMS of Sway

Narrow Stance

In ML directions for narrow stance no significant interaction was obvious (F(2,27) = 0.013, p = .875, ${\eta_p}^2$ = .010) for RMS of COP. The main effect of feedback was significant (F(1,27) = 10.90, p = .003, ${\eta_p}^2$ = .288), meaning that the availability of feedback went along with an increased RMS of sway. The main effect of group was not significant (F(2,27) = 0.20, p = .817, ${\eta_p}^2$ = .015) (Table A.4). Comparing feedback vs no feedback with t-tests indicated a significantly higher RMS in the *repulsive* group (t(9) = 2.57, p = .030, d_z = 0.815) when feedback was available. In the *no instruction* group a tendency towards less sway without feedback existed (t(9) = 2.18, p = .057, d_z = .692) (Figure 5.11(a) and Table A.6).



(a) (b)

Figure 5.11: RMS of COP in a) ML and b) AP directions for narrow stance; error bars represent the standard error of the mean; statistical significance indicated by †p < .1, *p < .05; n = 30.

In AP directions the pattern was similar. No significant interaction (F(2,27) = 0.49, p = .620, ${\eta_p}^2$ = .035) was found. Only feedback showed a significant main effect (F(1,27) = 14.28, p = .001, ${\eta_p}^2$ = .346). Again, with feedback a higher RMS of sway was observed. The main effect of group was not significant (F(2,27) = 0.21, p = .810, ${\eta_p}^2$ = .015) (Table A.4).

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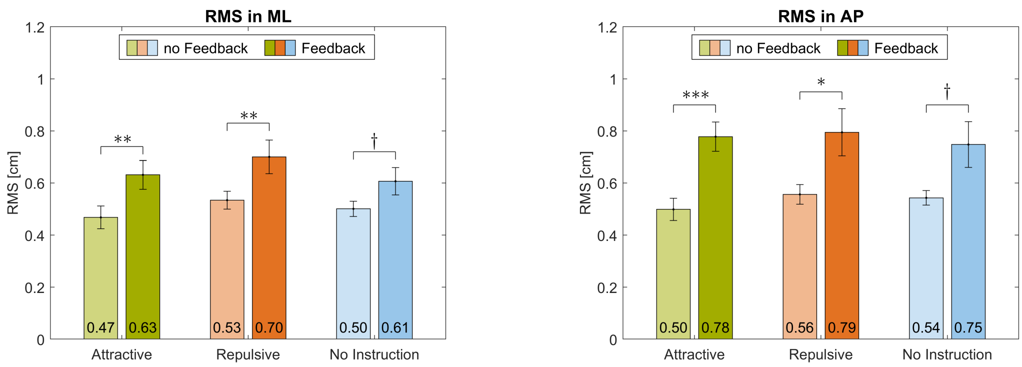
T-tests showed significant differences in the *attractive* (t(9) = 2.57, p = .030, d_z = .813)) and *no instruction* (t(9) = 2.56, p = .030, d_z = .810) group when comparing feedback and no feedback (Table A.6). Consequently, a higher RMS is obvious in case feedback was available (Figure 5.11(b)).

Investigating differences between groups for feedback and no feedback revealed no significant differences between groups in both directions (Table A.5).

Semitandem Stance

For standing in semitandem stance the same pattern as for narrow stance was obvious for RMS in ML directions. No interaction effect occurred (F(2,27) = 0.50, p = .615, $\eta_p{}^2$ = .035) for RMS of COP. The main effect of feedback was significant (F(1,27) = 26.84, p < .001, $\eta_p{}^2$ = .498). Consequently, with feedback a higher RMS of sway was observed. For the factor group no significant main effect was obvious (F(2,27) = 0.83, p = .449, $\eta_p{}^2$ = .058) (Table A.4). Equality of variances was not given in this case according to Levene test (p = .047).
T-tests showed that the RMS in ML directions was significantly higher with feedback compared to no feedback in the *attractive* (t(9) = 4.28, p = .002, d_z = 1.347) and *repulsive* (t(9) = 3.40, p = .008, d_z = 1.071) group. The *no instruction* group showed a tendency towards a higher RMS when feedback was available (t(9) = 1.87, p = .095, d_z = .592) (Figure 5.12(a) and Table A.6).



(a) (b)

Figure 5.12: RMS of COP in a) ML and b) AP directions for semitandem stance; error bars represent the standard error of the mean; statistical significance indicated by $^{\dagger}p < .1$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$; n = 30.

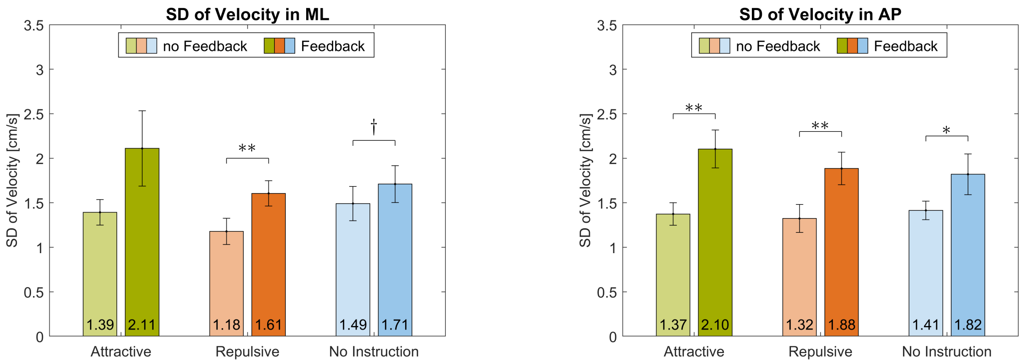
In AP directions there was again no significant interaction (F(2,27) = 0.25, p = .779, $\eta_p{}^2$ = .018) and no main effect of group (F(2,27) = 0.16, p = .856, $\eta_p{}^2$ = .011). However, the main effect of feedback was significant (F(2,27) = 31.67, p < .001, $\eta_p{}^2$ = .540) indicating that the RMS of sway was higher when feedback was available

compared to no feedback (Table A.4).
Feedback led to a higher RMS in the *attractive* ($t(9) = 5.63$, $p < .001$, $d_z = 1.777$) and *repulsive* ($t(9) = 3.23$, $p = .010$, $d_z = 1.017$) group compared to no feedback. In the *no instruction* group only a tendency towards this pattern was apparent ($t(9) = 2.21$, $p = .054$, $d_z = .700$) (Figure 5.12(b) and Table A.6).

Comparing the three different groups concerning feedback and no feedback by an ANOVA showed no significant differences between groups (Table A.5).

SD of Velocity

Narrow Stance
For the SD of velocity in ML directions no significant interaction ($F(2,27) = 0.25$, $p = 0.779$, ${\eta_p}^2 = .018$) was found between feedback and group for narrow stance. The main effect of group was not significant ($F(2,27) = 0.16$, $p = .856$, ${\eta_p}^2 = .011$), whereas the main effect of feedback was significant ($F(1,27) = 31.67$, $p = <.001$, ${\eta_p}^2 = .540$) (Table A.4). The SD of velocity is higher when feedback is available compared to no feedback.
When comparing feedback vs no feedback by means of t-tests, it became obvious that in the *repulsive* group the SD of velocity was significantly higher with feedback ($t(9) = 4.33$, $p = .002$, $d_z = 1.369$), whereas the *no instruction* group showed only a tendency towards this pattern ($t(9) = 2.24$, $p = .051$, $d_z = .708$) (Figure 5.13(a) and Table A.6).



(a) (b)

Figure 5.13: Standard deviation of velocity of COP in a) ML and b) AP directions for narrow stance; error bars represent the standard error of the mean; statistical significance indicated by $^{\dagger}p < .1$, $^{*}p < .05$, $^{**}p < .01$; $n = 30$.

In AP directions the same pattern was obvious. The interaction effect was not significant ($F(2,27) = 1.11$, $p = .343$, ${\eta_p}^2 = .076$) as well as the main effect of group

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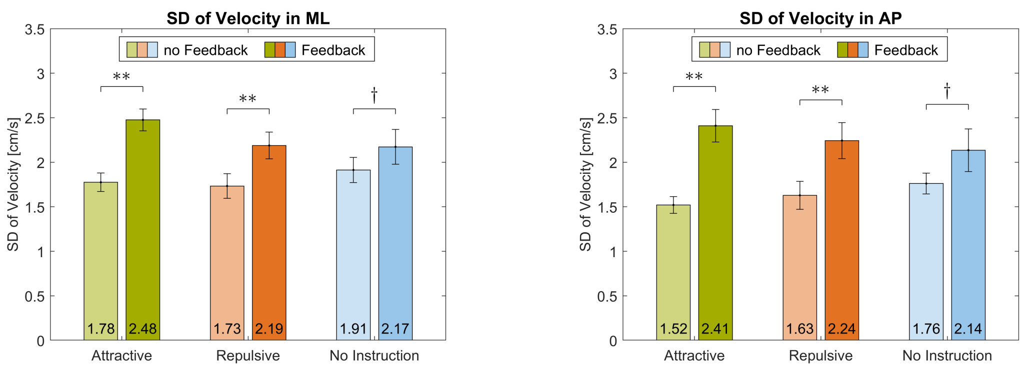
(F(2,27) = 0.23, p = .799, $\eta_p{}^2$ = .016). Only the factor feedback showed a significant main effect (F(1,27) = 4.58, p < .001, $\eta_p{}^2$ = .600) indicating an increase in SD of velocity when feedback was available (Table A.4).
T-tests showed that in the *attractive* (t(9) = 3.82, p = .004, d_z = 1.209), the *repulsive* (t(9) = 5.23, p = .001, d_z = 1.653) and in the *no instruction* (t(9) = 2.68, p = .025, d_z = .844) group the SD of velocity was higher with feedback compared to no feedback (Figure 5.13(b) and Table A.6).

No significant differences between groups for feedback as well as no feedback were found (Table A.5).

<u>Semitandem Stance</u>
No significant interaction occurred for the SD of velocity (F(2,27) = 2.81, p = .078, $\eta_p{}^2$ = .172) in ML directions. The main effect of feedback was significant (F(1,27) = 38.44, p < .001, $\eta_p{}^2$ = .587) indicating a higher SD of velocity with feedback compared to no feedback. The group factor did not show significant differences (F(2,27) = 0.41, p = .669, $\eta_p{}^2$ = .029) (Table A.4).
The SD of velocity was significantly higher in the *attractive* (t(9) = 4.93, p = .001, d_z = 1.559) and *repulsive* (t(9) = 3.48, p = .007, d_z = 1.099) group and tended to be higher in the *no instruction* group (t(9) = 2.14, p = .061, d_z = .675) with feedback compared to no feedback (Figure 5.14(a) and Table A.6).



(a) (b)

Figure 5.14: Standard deviation of velocity of COP in a) ML and b) AP directions for semitandem stance; error bars represent the standard error of the mean; statistical significance indicated by †p < .1, **p < .01; n = 30.

This pattern was also evident in AP directions. A non-significant interaction (F(2,27) = 1.96, p = .160, $\eta_p{}^2$ = .127) went along with a significant main effect of feedback (F(1,27) = 34.75, p < .001, $\eta_p{}^2$ = .563) and a non-significant main effect of group (F(2,27) = 0.10, p = .990, $\eta_p{}^2$ = .001) (Table A.4). Consequently, SD of

velocity was higher when feedback was available compared to no feedback.
T-tests showed a significantly higher SD of velocity for the *attractive* ($t(9) = 4.59$, $p = .001$, $d_z = 1.452$) and *repulsive* ($t(9) = 3.78$, $p = .004$, $d_z = 1.196$) group and a tendency towards this pattern in the *no instruction* group ($t(9) = 1.93$, $p = .085$, $d_z = .612$) when comparing feedback and no feedback (Figure 5.14(b) and Table A.6).

The ANOVA between groups for feedback and no feedback showed no significant differences in ML and AP directions (Table A.5).

These results show that with feedback RMS of sway and SD of velocity of COP were higher compared to the no feedback condition. In general, these differences seemed to be more pronounced in the *attractive* and *repulsive* group. This first part of the results gave insights in objective measures to quantify sway, whereas in the following section the subjective perception of the participants is presented.

5.2.3 Intuitiveness of Group

An univariate ANOVA was calculated to determine differences between the three groups in the ratings for the *QUESI score* and its subitems to assess the intuitiveness of our different configurations of feedback. Consequently, these results are linked to the second hypothesis if the type of instruction influenced the intuitiveness.
For the *QUESI score* ($F(2,27) = 3.04$, $p = .064$, $\eta_p^2 = .184$) a tendency for significant differences between groups existed. The *repulsive* group tended to rate the intuitiveness of the feedback higher compared to the *no instruction* group ($p = .077$).
For the item *Subjective Mental Workload* ($F(2,27) = 2.77$, $p = .081$, $\eta_p^2 = .170$), there was again a tendency for significant differences. However, post hoc test showed no tendencies and significances.
For the item *Perceived Effort of Learning* ($F(2,27) = 3.65$, $p = .040$, $\eta_p^2 = .213$) a significant ANOVA occurred with significant differences between the *repulsive* and *no instruction* group ($p = .040$). The *repulsive* group rated the intuitiveness higher compared to the *no instruction* group.
The ANOVA for *Familiarity* ($F(2,27) = 3.61$, $p = .041$, $\eta_p^2 = .211$) was significant as well, however, the Bonferroni post hoc tests were not significant. Only the comparison between the *repulsive* and *no instruction* group showed a tendency towards higher ratings given by the *repulsive* group ($p = .066$).
The items *Perceived Achievement of Goals* ($F(2,27) = 0.40$, $p = .675$, $\eta_p^2 = .029$) and *Perceived Error Rate* ($F(2,27) = 0.34$, $p = .716$, $\eta_p^2 = .024$) showed no significant differences between groups.
When looking at the mean values, it was obvious that the *repulsive* group gave the highest ratings, followed by the *attractive* group, apart from the item *Subjective Mental Workload*. Overall, the *no instruction* group rated with the lowest scores (Figure 5.15).

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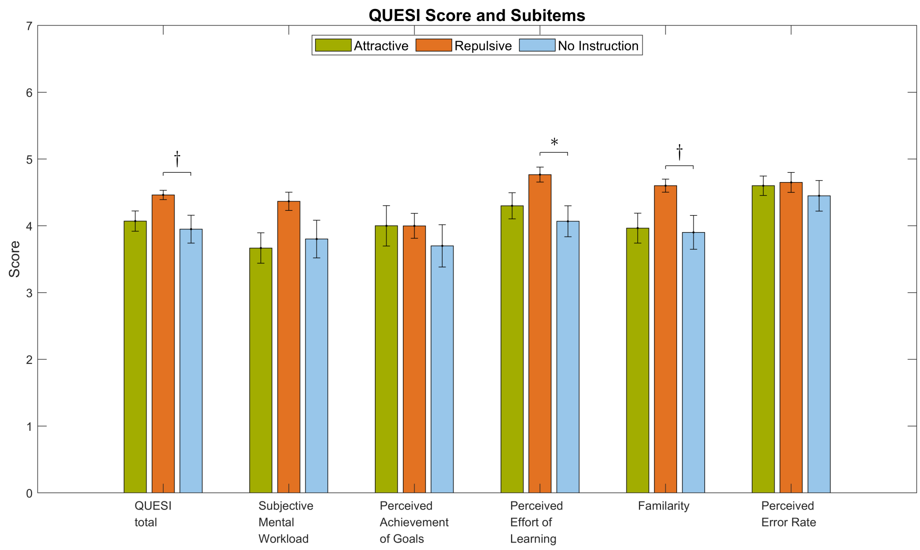


Figure 5.15: QUESI score and its subitems; error bars represent the standard error of the mean; statistical significance indicated by $^{\dagger}p < .1$, $^{*}p < .05$; n = 30.

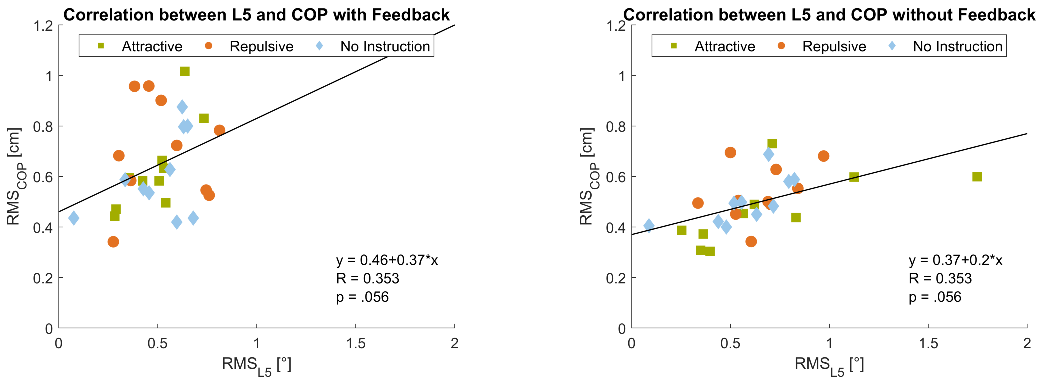
5.3 Correlation between COP and L5

To investigate the relationship between movements of COP and L5, Pearson correlations were calculated for the different parameters and feedback and no feedback. This analysis contributed to the third hypothesis, whether vibrotactile feedback influenced the correlation between COP and L5. For all parameters, apart from RMS in AP and the SD of velocity in ML for narrow stance, the correlation coefficient was lower for feedback compared to no feedback (Table 5.2).

Table 5.2: Correlation between COP and L5 sway parameters for feedback and no feedback; NS = narrow stance; ST = semitandem stance; statistical significance indicated by $^{\dagger}p < .1$, $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Parameter	Stance	Feedback	no Feedback
RMS in ML	NS	0.643^{***}	0.681^{***}
	ST	$0.353^{\dagger}$	0.539^{**}
RMS in AP	NS	0.244	0.179
	ST	0.066	0.220
SD of velocity in ML	NS	0.872^{***}	0.816^{***}
	ST	0.562^{**}	0.717^{***}
SD of velocity in AP	NS	0.520^{**}	0.624^{***}
	ST	0.392^{*}	0.617^{***}

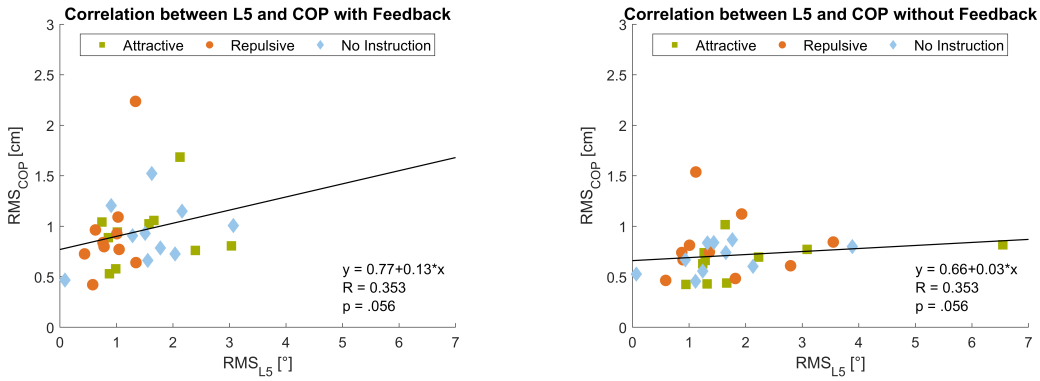
Figure 5.16 shows the correlation of the RMS of sway in ML directions between L5 and COP for semitandem stance with and without feedback. If feedback was available a moderate correlation consisted, whereas without feedback COP and L5 were strongly associated.



(a) (b)

Figure 5.16: Correlation between RMS of sway in ML directions between L5 and COP for semitandem stance a) with feedback and b) without feedback; the black line represents the regression line.

This pattern was also evident for the SD of velocity in AP directions. For all remaining parameters, apart from RMS in AP, there was a strong correlation between L5 and COP, in most cases with a slightly higher R-value for no feedback (RMS in ML for narrow stance, SD of velocity in ML for narrow stance & semitandem stance, SD of velocity in AP for narrow stance). The correlation of the RMS in AP directions was small as well for feedback as for no feedback and both stances. In narrow stance the R-value was slightly higher with feedback compared to no feedback (Figure 5.17). Overall, the correlation between COP and L5 parameters tended to be lower for feedback compared to no feedback.



(a) (b)

Figure 5.17: Correlation between RMS of sway in AP directions between L5 and COP for narrow stance a) with feedback and b) without feedback; the black line represents the regression line.

5.4 Learning

Mixed model ANOVAs were calculated over the seven trials with and without feedback, as it was expected that subjects familiarize over time with the feedback. First, the results of L5 are presented followed by COP. For L5, again, the amount of changes and the percentage above threshold are considered. This sections aims to answer the fourth hypothesis if a learning effect occurred over the seven trials.

5.4.1 L5

When looking at the the results of the ANOVAs for L5 data, in general, only few significant differences occurred. In most cases there was a random pattern over the trials in all three groups for feedback as well as for no feedback.

This pattern is exemplary shown for the SD of velocity in AP directions for narrow stance. For feedback and no feedback the interaction effect (feedback: F(8.41,113.52) = 1.55 (GG.), p = .112, $\eta_p{}^2$, .103; no feedback: F(6.88,92.93) = 0.71 (GG.), p = .659, $\eta_p{}^2$ = .050), the main effect of trial (feedback: F(4.20,113.52) = 1.66 (GG.), p = .161, $\eta_p{}^2$ = .058; no feedback: F(3.44,92.93) = 1.92 (GG.), p = .123, $\eta_p{}^2$ = .066) and the main effect of group (feedback: F(2,27) = 0.92, p =.413, $\eta_p{}^2$ = .063; no feedback: F(2,27) = 0.53, p = .597, $\eta_p{}^2$ = .037) were not significant (Figure 5.18). All other parameters show a similar pattern apart from two exceptions (RMS in AP of narrow stance with feedback, SD of velocity in ML of narrow stance without feedback), which are presented in the following, and some tendencies (Table A.7).

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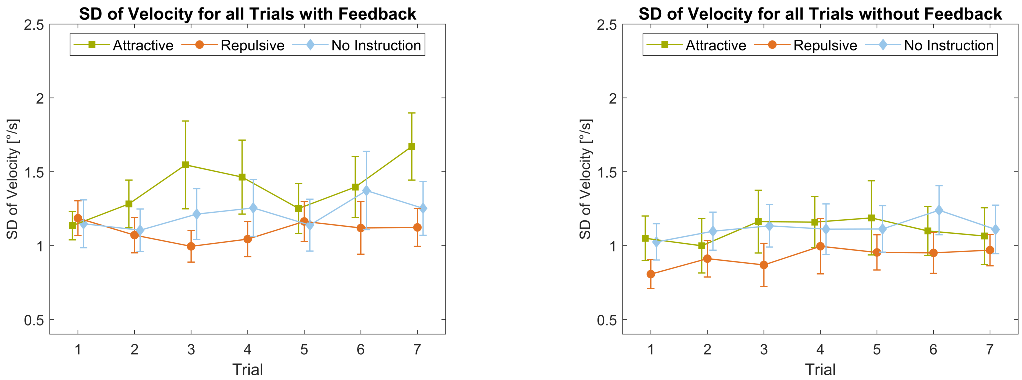
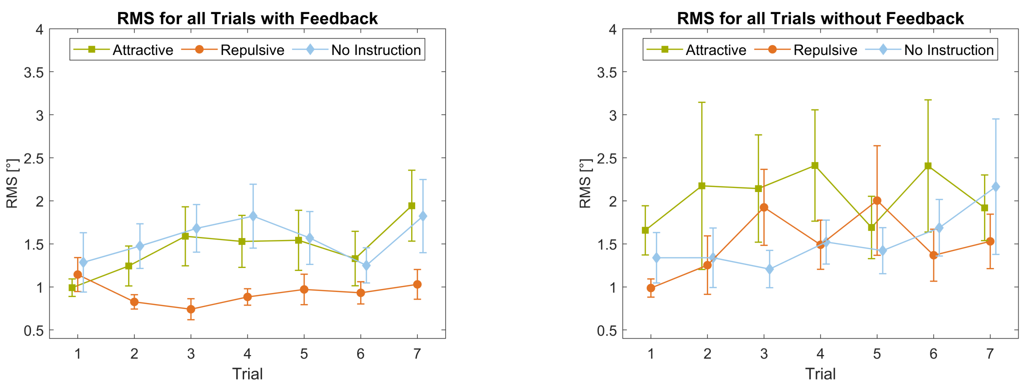


(a) (b)

Figure 5.18: Progression of standard deviation of velocity (L5) in AP directions for narrow stance over all seven trials a) with feedback and b) without feedback; error bars represent the standard error of the mean; n = 30.

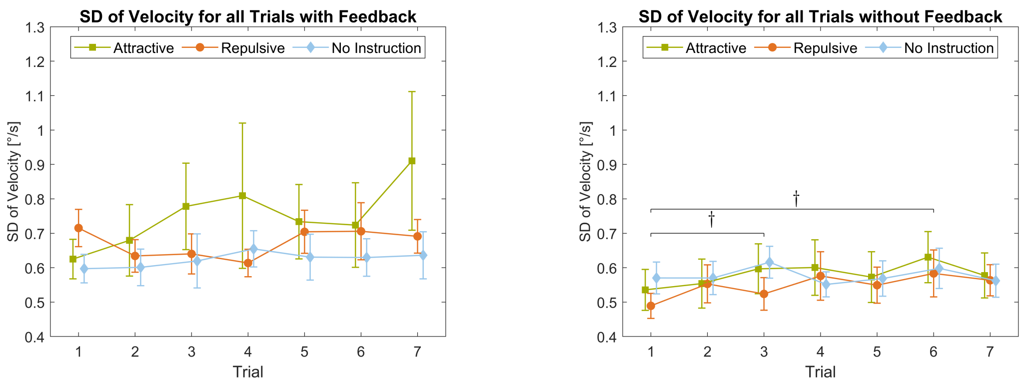
The RMS in AP directions for narrow stance with feedback showed no significant interaction effect (F(8.52,115.07) = 1.04 (GG.), p = .412, $\eta_p{}^2$ = .072). However, the main effect of trial (F(4.26,115.07) = 2.03 (GG.), p = .091, $\eta_p{}^2$ = .070) and group (F(2,27) = 2.90, p = .072, $\eta_p{}^2$ = .070) showed a tendency towards significant differences. Post hoc tests only revealed a tendency towards differences between the *repulsive* and the *no instruction* group (p = .098) (Figure 5.19(a)). Without feedback the interaction effect (F(8.35,112.78) = 0.94 (GG.), p = .489, $\eta_p{}^2$ = .065), the main effect of trial (F(4.18,112.78) = 0.88 (GG.), p = .482, $\eta_p{}^2$ = .032) and group (F(2,27) = 0.77, p = .475, $\eta_p{}^2$ = .054) were not significant (Figure 5.19(b)).



(a) (b)

Figure 5.19: Progression of RMS (L5) in AP directions for narrow stance over all seven trials a) with feedback and b) without feedback; error bars represent the standard error of the mean; n = 30.

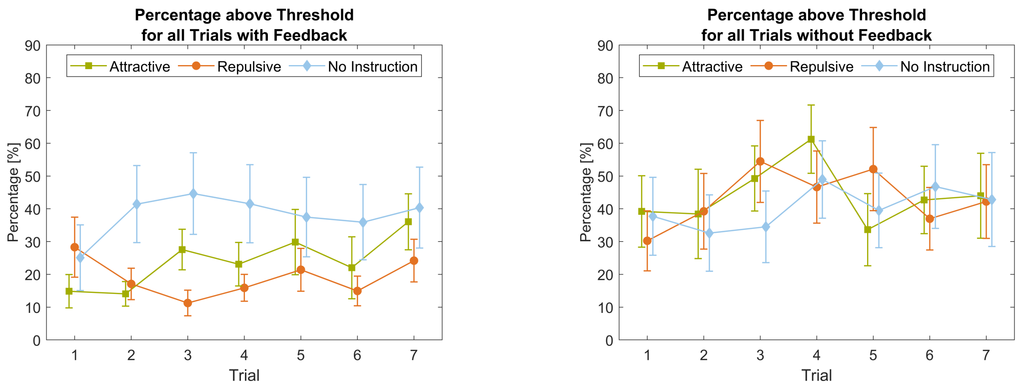
In ML directions for SD of velocity in narrow stance, in case feedback was available, again the interaction effect (F(5.97,80.59) = 1.08 (GG.), p = .380, $\eta_p{}^2$ = .074), the main effect of trial (F(2.99,80.59) = 1.17 (GG.), p = .328, $\eta_p{}^2$ = .041) and group (F(2,27) = 0.65, p = .528, $\eta_p{}^2$ = .460) were not significant (Figure 5.20(a)). However, without feedback the main effect of trial became significant (F(6,162) = 3.53, p = .003, $\eta_p{}^2$ = .166), whereas the interaction effect (F(12,162) = 1.34, p = .200, $\eta_p{}^2$ = .090) and the main effect of group (F(2,27) = 0.10, p = .904, $\eta_p{}^2$ = .007) were not significant. Consequently, there was a tendency towards a higher SD of velocity in trial 3 (p = .070) and 6 (p = .066) compared to trial 1, supported by Bonferroni post hoc tests (Figure 5.20(b)).



(a) (b)

Figure 5.20: Progression of standard deviation of velocity (L5) in ML directions for narrow stance over all seven trials a) with feedback and b) without feedback; error bars represent the standard error of the mean; statistical significance indicated by $^{\dagger}p < .1$; n = 30.

For L5, additionally, the amount of changes and the percentage above threshold were investigated. No significant interaction and main effects for both stances and either feedback or no feedback occurred (Table A.7). Figure 5.21 shows this pattern for the percentage above threshold in ML directions for narrow stance.



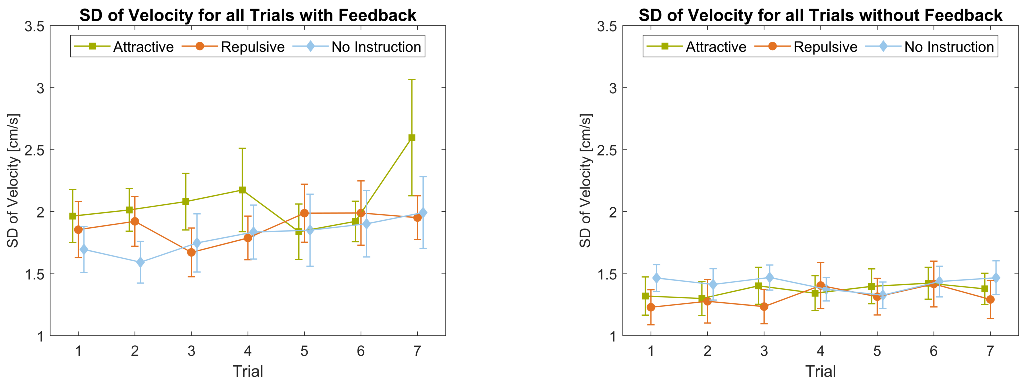
(a) (b)

Figure 5.21: Progression of percentage above threshold (L5) in ML directions for narrow stance over all seven trials a) with feedback and b) without feedback; error bars represent the standard error of the mean; n = 30.

5.4.2 COP

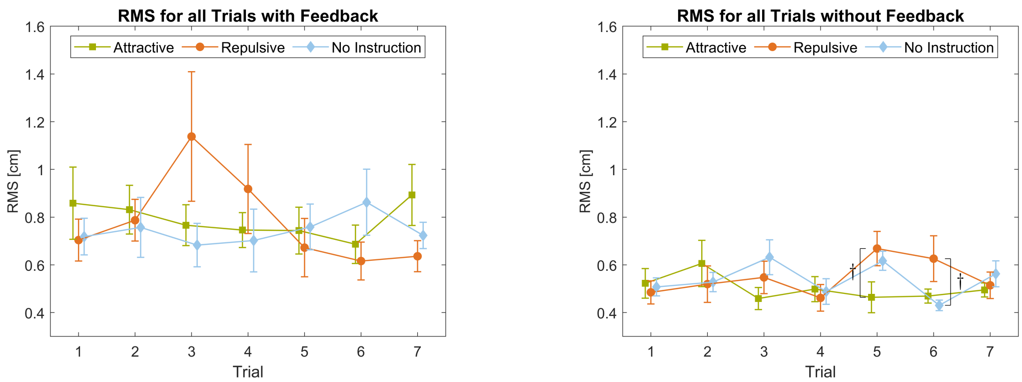
For COP, too, only very few significant effects and tendencies of trial and group occurred. Overall, no decreases or improvements in performance were visible. Furthermore, groups seemed to be comparable in terms of their results for sway parameters. This pattern is, again, exemplary shown for the SD of velocity in AP directions for narrow stance. Neither a significant interaction (feedback: F(5.18,69.90) = 0.96 (GG.), p = .448, $\eta_p{}^2$ = .067; no feedback: F(7.92,106.87) = 1.26 (GG.); p = .273, $\eta_p{}^2$ = .085), nor a significant main effect of trial (feedback: F(2.59,69.90) = 1.71 (GG.), p = .121, $\eta_p{}^2$ = .060; no feedback: F(3.96,106.87) = 1.03 (GG.), p = .408, $\eta_p{}^2$ = .037) or a significant main effect of group (feedback: F(2,27) = 0.57, p = .575, $\eta_p{}^2$ = .040; no feedback: F(2,27) = 0.18, p = .834, $\eta_p{}^2$ = .013) occurred (Figure 5.22). This pattern was also obvious for nearly all other parameters apart from some exceptions (RMS in AP of semitandem stance without feedback, RMS in ML of narrow stance without feedback & SD of velocity in ML of narrow stance without feedback) which are mentioned in the following. The results for all parameters and conditions are shown in Table A.8).

For the RMS in AP directions of semitandem stance, a significant interaction for no feedback (F(12,162) = 1.91, p = .036, $\eta_p{}^2$ = .124) and a tendency towards a significant interaction for feedback (F(8.19,110.51) = 1.80 (GG.), p = .082, $\eta_p{}^2$ = .118) were evident. Analysing the simple main effects of group revealed no differences for the between-subject factor group (Table A.9) and the within-subject factor trial (Table A.10). The main effects of feedback were not significant neither (trial: F(4.09,110.51) = 0.69 (GG.), p = .662, $\eta_p{}^2$ = .025; group: F(2,27) = 0.10, p = .901, $\eta_p{}^2$ = .008). For no feedback, however, there was a tendency towards a significant influence of group at T5 (F(2,27) = 3.11, p = .061, ${\eta_p}^2$ = .187) between the *attractive* and the *repulsive* (p = .071) group and at T6 (F(2,27) = 3.06, p = .063, ${\eta_p}^2$ = .185) between the *repulsive* and the *no instruction* (p = .081) group. Furthermore, there was a significant influence of trial in the *no instruction* group (F(6,54) = 2.64, p = .026, ${\eta_p}^2$ = .227). Post hoc tests, however, did not show any significant differences or tendencies (Figure 5.23).



(a) (b)

Figure 5.22: Progression of standard deviation of velocity (COP) in AP directions for narrow stance over all seven trials a) with feedback and b) without feedback; error bars represent the standard error of the mean; n = 30.



(a) (b)

Figure 5.23: Progression of RMS (COP) in AP directions for semitandem stance over all seven trials a) with feedback and b) without feedback; error bars represent the standard error of the mean; statistical significance indicated by †p < .1; n = 30.

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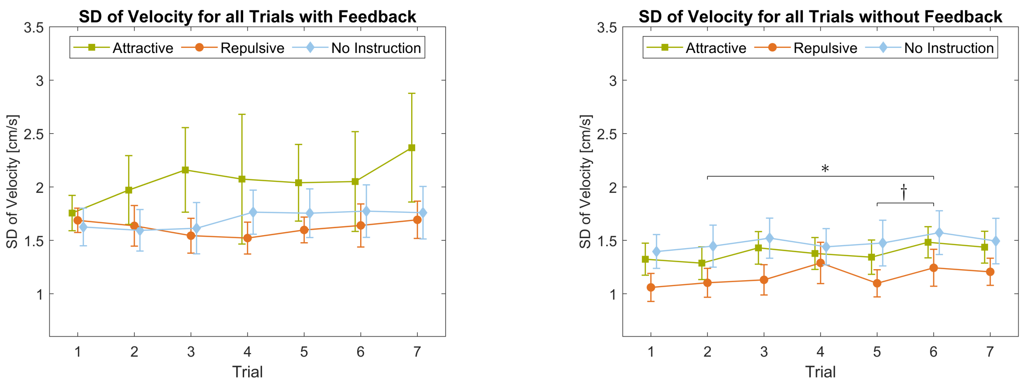
For the RMS in ML directions of narrow stance a significant interaction occurred for no feedback (F(12,162) = 1.90, p = .038, $\eta_p{}^2$ = .123). Further investigation of the simple main effects revealed no differences between groups (Table A.9). However, the factor trial had a significant effect in group *repulsive* (F(6,54) = 3.59, p = .005, $\eta_p{}^2$ = .285). There tended to be a higher RMS in trial 4 compared to trial 1 (p = .052). Additionally, in trial 5 the RMS was significantly smaller compared to trial 4 (p = .004) (Table A.10). The main effect of trial (F(6,162) = 1.31, p = .256, $\eta_p{}^2$ = .123) and group (F(2,27) = 0.45, p = .643, $\eta_p{}^2$ = .032) were not significant.

The SD of velocity in ML directions of narrow stance for feedback showed no significant interaction (F(5.84,78.90) = 0.57 (GG.), p = .753, $\eta_p{}^2$ = .040), nor a significant main effect of trial (F(2.92,78.90) = 0.78 (GG.), p = .507, $\eta_p{}^2$ = .028) or group (F(2,27) = 0.86, p = .435, $\eta_p{}^2$ = .060) (Figure 5.24(a)). For no feedback the interaction (F(8.61,116.28) = 0.78 (GG.), p = .628, $\eta_p{}^2$ = .055) and the main effect of group (F(2,27) = 1.05, p = .365, $\eta_p{}^2$ = .072) were again not significant. However, across all groups, significant differences were obvious for trial 2 and 6 (p = .019) and a tendency towards trial 5 and 6 (p = .077) (Figure 5.24(b)).



(a) (b)

Figure 5.24: Progression of standard deviation of velocity (COP) in ML directions for narrow stance over all seven trials a) with feedback and b) without feedback; error bars represent the standard error of the mean; statistical significance indicated by †p < .1, *p < .05; n = 30.

Overall, it can be summarized that neither for L5 nor for COP a learning effect was obvious. Furthermore, no decrease in performance was evident.

5.5 Correlation between Baseline Sway and Proportional Reduction

To investigate a possible effect of the amount of baseline sway on the proportional reduction in sway parameters while using feedback compared to no feedback (fifth hypothesis), Pearson correlations were calculated for both stances, RMS and SD of velocity for COP and L5, respectively. An overview over all correlations can be found in Table 5.3.

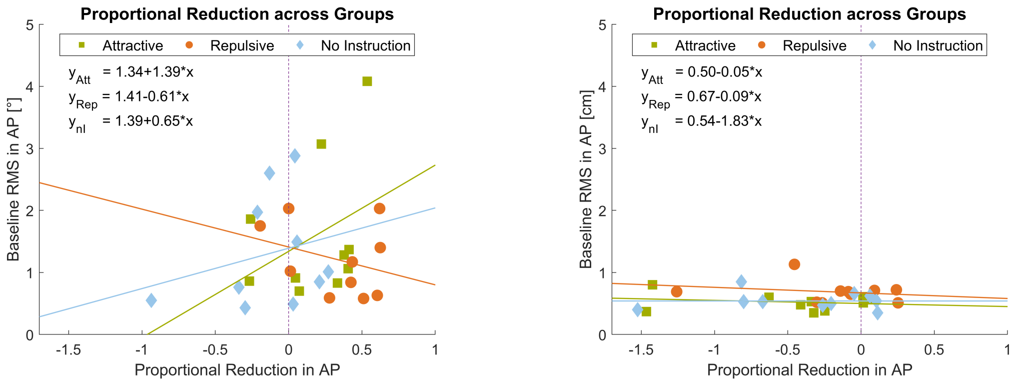
Table 5.3: Correlation according to Pearson (R-values) between baseline sway and proportional reduction of sway parameters for L5 and COP; positive values indicate a positive correlation and negative values a negative correlation; statistical significance indicated by $^{\dagger}p<.01$, $^{*}p<.05$.

		L5			**COP**		
		Att	*Rep*	*nI*	*Att*	*Rep*	*nI*
RMS in ML	NS	0.37	−0.43	$0.51^{\dagger}$	0.33	0.44	0.04
	ST	0.19	−0.36	−0.23	0.29	−0.27	−0.26
RMS in AP	NS	0.35	−0.31	0.25	−0.19	−0.21	−0.001
	ST	$-0.44^{\dagger}$	0.06	0.08	−0.02	−0.36	-0.58^{*}
SD of velocity in ML	NS	0.18	$0.51^{\dagger}$	−0.37	0.07	0.55^{*}	0.00
	ST	$0.50^{\dagger}$	0.29	0.07	$0.46^{\dagger}$	0.42	−0.17
SD of velocity in AP	NS	0.42	0.20	−0.26	$0.55^{\dagger}$	0.63^{*}	−0.32
	ST	0.38	0.35	−0.47	$0.55^{\dagger}$	0.22	-0.56^{*}

Explanations: Att = Group attractive; Rep = Group repulsive; nI = Group no instruction; NS = narrow stance; ST = semitandem stance.

First, the results of narrow stance are presented for RMS. In AP directions the *attractive* and *no instruction* group showed a positive correlation for L5,. This means that the higher the baseline sway was the higher the proportional reduction seemed to be. The correlation for the *repulsive* group was negative (Figure 5.25(a)). The higher the baseline sway was the smaller the proportional reduction seemed to be. For COP a negative correlation was evident for the *attractive* and *repulsive* group. There was no correlation for the *no instruction* group (Figure 5.25(b)).

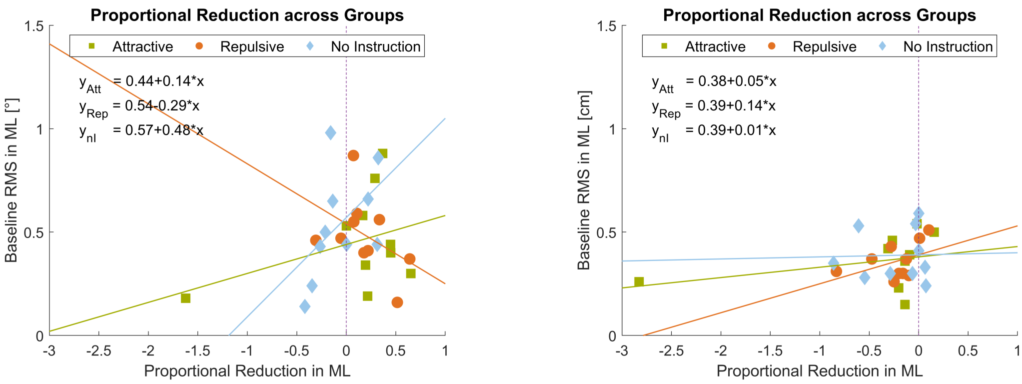
In ML directions, again, there was a positive correlation in the *attractive* and the *no instruction* group and a negative in the *repulsive* group for L5 (Figure 5.26(a)). For COP, the baseline RMS value of the *attractive* and the *repulsive* group correlated positively with the proportional reduction, whereas there was no correlation evident in the *no instruction* group (Figure 5.26(b)).



(a) (b)

Figure 5.25: Correlation between proportional reduction and baseline RMS in AP directions for narrow stance of a) L5 and b) COP; the colored lines represents the regression lines; n = 30.

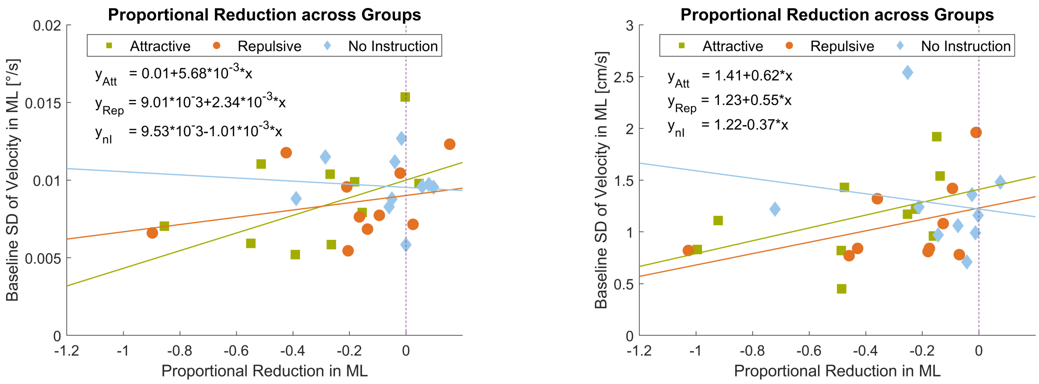
For semitandem stance in AP directions there was a negative correlation for the *attractive* group only. The two other groups showed no cohesion of those two measures. However, in ML directions a positive correlation was evident for the *attractive* group, whereas in the *repulsive* and the *no instruction* groups baseline sway and the proportional reduction were negatively correlated. For COP the *repulsive* and the *no instruction* group showed negative correlations in both directions. The *attractive* group, however, showed a positive correlation in ML and no correlation in AP directions.



(a) (b)

Figure 5.26: Correlation between proportional reduction and baseline RMS in ML directions for narrow stance of a) L5 and b) COP; the colored lines represents the regression lines; n = 30.

The analysis of the correlation between baseline SD of velocity and proportional reduction revealed for L5 as well as for COP a similar pattern in both directions (ML and AP) and stances. For the *attractive* and *repulsive* group always a low, moderate or strong positive correlation was visible for COP and L5, apart from narrow stance in ML directions of COP.
For the *no instruction* group either no or a negative correlation was evident (Table 5.3). Figure 5.27 shows this pattern exemplarily for semitandem stance in ML directions. Consequently, a lower baseline SD of velocity went along with a greater increase in SD of velocity when feedback was used in the *attractive* and the *repulsive* group. In the *no instruction* group the pattern was vice versa for narrow stance in both directions and stances, apart from semitandem stance in ML (L5) and narrow stance in ML directions (COP).



(a) (b)

Figure 5.27: Correlation between proportional reduction and baseline standard deviation of velocity in ML directions for semitandem stance of a) L5 and b) COP; the colored lines represents the regression lines; n = 30.

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Chapter 6

Discussion

This work aimed to investigate how a vest providing vibrotactile biofeedback influences human postural control and what kind of stimulus is more effective and subjectively more intuitive in healthy young adults. Therefore, we compared three different types of instructions (*attractive*: move in the direction of feedback, *repulsive*: move in the opposite direction of feedback and *no instruction* with attractive stimulus).
We expected that the vest would decrease sway parameters for L5 and COP and expected differences between the three instruction groups. In this chapter, first, the influences of feedback and group are discussed. Then, the correlation between COP and L5 parameters, a potential learning effect over seven trials, and the correlation between baseline sway and proportional reduction to possibly identify subjects improving to a higher extent are integrated into the context of the current literature. Lastly, the limitations of the study are elaborated and suggestions for further research are given.

6.1 Influence of Feedback

In the following, the results of this study are compared with recent literature in terms of the effectiveness of the feedback. First, this is done for L5 and COP, separately. Then, the results are brought together. Lastly, results are linked with the phenomenon of light touch. Thereby, the focus lays on the interpretation of the mixed model ANOVAs and their main effect of feedback. The differences between groups are discussed afterwards (see section '6.2 Influence of Group').

6.1.1 L5

For L5, following the expectations, RMS of sway was decreased in ML and AP directions for narrow stance and semitandem stance by vibrotactile feedback (see section '5.2.1 RMS of Sway') and a significantly higher SD of velocity was found (see section '5.2.1 SD of Velocity'). Additionally, significantly more changes occurred for narrow stance only in ML directions and semitandem stance only in AP directions

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with feedback according to the mixed model ANOVA (see section '5.2.1 Amount of Changes'). Feedback decreased the percentage above threshold for both stances in both directions (see section '5.2.1 Percentage above Threshold').

In the following, several studies which could also show a decrease in angle parameters related to postural control in case feedback was available compared to no feedback are described.
Healthy subjects decreased their SD of body tilt, which is as well as the RMS a variability measure, in ML and AP direction as indicated by an IMU at the lower torso due to vibrotactile feedback [BCMS13]. Motors were placed around the lower torso and provided vibrotactile biofeedback in the ML and AP axes [BCMS13].
The cell phone-based balance trainer of Lee and colleagues [LKCS12] can only give feedback in two axes, either AP or ML, and is referenced to an accelerometer at the waist. The device was tested in different stance positions (Romberg, semitandem and tandem stance). Depending on the stance, the motors were placed for Romberg stance at the navel and spine, whereas for semitandem and tandem stance motors were located at the medial and lateral side of the trunk. Stance dependent thresholds based on the angle displacement were used for all subjects. In healthy subjects, for Romberg and tandem stance RMS in AP and ML as well as the elliptical area were decreased when feedback was available. For semitandem stance only RMS in ML, which was the axis feedback was given in, and the elliptical area were lower compared to standing without feedback. Subjects with vestibular deficits were only tested in semitandem stance. They also showed a significant decrease in RMS in ML and elliptical area. Consequently, mainly sway reductions in the axis of feedback were found. Closing the eyes led to a smaller postural control in general [LKCS12].
Our study demonstrated that feedback in all four directions is effective in decreasing RMS of L5 in all four directions. This might especially be beneficial for individuals with balance disorders, as patients recently only showed improvements in the direction in which feedback was provided in by a balance trainer [LKCS12].
The vibrotactile device of Wall et al. [WWSK01] provided vibrotactile feedback also only in one axis, in ML directions. The motors were either placed on the shoulder or the sides of the trunk, whereas the IMU as a reference for the feedback was placed at the head. As soon as head tilt angle exceeded 0.5° feedback was given. Wall et al. [WWSK01] showed that the RMS of head tilt was decreased for both placement locations of the motors, with the shoulder positioning being slightly superior compared to the sides of the trunk. Even though only being able to give feedback in ML directions, these results confirmed that positioning the motors on the upper torso can be effective in improving balance. Furthermore, they demonstrated that the motors and the sensor where the feedback is referenced to do not necessarily need to be at the same height, as they used head tilt for their feedback at the shoulders or trunk.
Moreover, also in auditory feedback two-directional feedback in ML axis referenced to an IMU at the lower body decreased RMS of trunk tilt in ML direction in tandem

stance in young [FFG+13] and older subjects [FMF+13].
Auditory feedback in all four directions referenced to an IMU reduced the range of trunk tilt and its variance [CCP+18]. However, the feedback only gave information about the strength of the deviation from a stable equilibrium, not about the direction [CCP+18].

The SD of velocity was included in the analysis of this study to not only get insights into the trajectory but also the velocity profile. For assessing standing balance, this parameter is amongst the most frequently used [GGP+19], whereby a small velocity goes along with better postural control [PN15]. However, according to the best of our knowledge, it has not been investigated in the research of vibrotactile feedback, yet.
The following paragraph considers recent studies investigating parameters related to velocity to integrate our results for the SD of velocity into current literature. One study investigated angular velocities near COM [NMAP+12]. However, it needs to be considered that the balance device was used in individuals with Parkinson disease only for training and not for the assessment of balance with feedback compared with no feedback. Training with vibrotactile feedback based on angular velocities led to reduced roll and pitch sway angular velocities compared to baseline during a post-training assessment without feedback. Additionally, the experimental group showed better balance compared to a control group, especially for the roll angle [NMAP+12]. Our results, however, showed a significantly higher SD of velocity with feedback compared to no feedback. Possibly, training or real-time feedback increases the SD of velocity due to a reaction to the cues, but after the training and during a balance assessment without feedback, subjects might be able to stand with a reduced velocity [NMAP+12]. Training could possibly help subjects to become more conscious about their sway and consequently remain within narrower boundaries and thus have to adapt their posture less often.
When considering the velocity profile during the trials, the study of Ballardini and colleagues [BFC+20] needs to be taken into account even though they only assessed the amplitude of acceleration and the frequencies of the signal, however, not the velocity. The feedback, which was only given in AP directions and referenced to the accelerations of an IMU at the lower torso, decreased the amplitude of acceleration only in AP axis. The increased frequency indicated a reduction of postural sway through smaller and more frequent postural corrections [BFC+20].
We did not investigate the acceleration profile of our data. However, the results would suggest that a higher SD of velocity due to the feedback would also go along with greater accelerations. Nevertheless, possibly also more frequent adaptations of posture due to feedback could explain this pattern. In our results, the increased amount of changes between 'on' and 'off' of the feedback, at least in some conditions, indicates that subjects adapt their posture more often. Also, Lee et al. [LKCS12] suggested that feedback induced more frequent adaptations of posture, as subjects aimed to stay below the body sway threshold. Moreover, no position parameter

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was presented in the study of Ballardini and colleagues, which makes it difficult to compare the results in more detail.
Through smaller and more frequent postural corrections [LKCS12,KHG93] (see Figure 5.2) feedback could have reduced lower trunk deviations. Krizková et al. [KHG93] explained increases in sway mean velocity and power spectrum density in the frequency range of 0.4 to 1.5 Hz by a higher activity of muscles in the ankle joint due to the feedback. They provided healthy subjects with visual feedback of their COP represented by a moving light on a screen. Probably, feedback provokes actions of the postural muscles, which influence process of acceleration and deceleration of quiet standing [KHG93]. This means that the vibrations might have induced kind of perturbations in the constant process of quiet standing.
The fact that feedback led to a higher velocity of trunk tilt in the axis of feedback was also evident in the study of Huffman et al. [HNAA10], who investigated multimodal feedback with the BalanceFreedom™, which also incorporates vibrotactile cues. They attributed this to an increased stiffness.

In the following, we give a further possible explanation for the increase in SD velocity in case feedback was available. Therefore, processes of normal quiet standing need to be understood. During quiet standing, individuals are steadily swaying back and forth. The movement is characterised by a constant process of acceleration and deceleration in clock- and counter-clockwise directions [Win95]. Consequently, the velocity is maximum when the displacement is zero. When the displacement reaches the maximum, the velocity is zero [WPP+98]. The COP of the left and right foot are moving in phase in AP directions, whereas in ML directions they are out of phase [Win95].
The increased SD of velocity could be explained by the active response of the subjects to the stimuli, as we explicitly instructed the subjects to compensate the vibrations, which was comparably done in other studies [LKCS12,LWL+15]. So, sudden reactions might have increased the variability in velocity.

In our pilot study the amount of changes between 'on' and 'off' of the vibrations was already used to identify an adequate formula for providing vibrotactile feedback. In the literature this parameter is not yet investigated and therefore cannot be classified. The amount of changes only significantly differed for narrow stance in ML directions and semitandem stance in AP directions. In general, approximately one to two changes more were present with feedback over a period of 40 seconds compared to no feedback. It seems logical that feedback induces more changes as the goal of the feedback is to remind subjects to move back below the individual body sway threshold. However, the difference between both modalities (feedback vs no feedback) was not as pronounced as compared to the other parameters.

A further indicator to evaluate the effectiveness of vibrotactile feedback represents the percentage above threshold. The measure is either indicated as percentage above

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threshold (fraction over threshold [WWSK01]) or percentage below threshold (percent time spent in the no-feedback zone [BCMS13] or percent time spent in the dead zone (in which tactors are not activated) [LKCS12]). For easier comparison with other studies all values in the following are claimed as percentage above threshold.

Bechly et al. [BCMS13] measured for subjects with peripheral vestibular deficit for the percentage above threshold ~70 % (standard error: 6 %) without and ~10 % (3 %) with feedback, whereas for healthy subjects values of ~55 % (6 %) were determined without feedback and ~10 % (1 %) with feedback.

In the study of Lee and colleagues [LKCS12] the percentage above threshold was also higher without feedback compared to with feedback. In healthy subjects, for Romberg it was reduced from ~60 % (6 %) to ~15 % (3 %), for semitandem from ~65 % (5 %) to ~5 % (1 %) and for tandem stance from ~40 % (6 %) to ~5 % (1 %) with closed eyes. Subjects with vestibular deficit, on the other hand, can reduce this parameter in semitandem stance with open eyes from ~20 % (4 %) to ~5 % (1 %) and with closed eyes from ~30 % (4 %) to ~10 % (1 %).

In our study, the percentage above threshold was reduced from 46 % (20 %) to 25 % (19 %) in the *attractive*, from 42 % (22 %) to 23 % (15 %) in the *repulsive*, and from 38 % (27 %) to 34 % (29 %) in the *no instruction* group if feedback was provided. In general, we found a significant reduction but not as large as in the above-mentioned studies (see section '5.2.1 Percentage above Threshold').

A possible explanation why our feedback did not induce such a great reduction could be the body sway threshold upon which feedback was provided. Lee and colleagues [LKCS12] chose 1° (Romberg in AP and semitandem stance in ML) and 1.5° (tandem stance in ML) with closed eyes, whereas Bechly et al. [BCMS13] used 1° in both axis for tandem Romberg stance with eyes open. In our study, especially in ML directions, the body sway threshold was smaller ($0.6 \pm 0.3°$) which means that it was harder to stay below the threshold.

In the study of Wall and colleagues [WWSK01] a body sway threshold of 0.5° in ML directions, the axis of feedback, was used, which was even smaller than our average body sway threshold over all subjects. In the same stance configuration as in our study, semitandem stance with feet 2.5 cm apart and closed eyes, they found a reduction in the percentage above threshold from ~65 % (5 %) to ~38 % (3 %) when applying the feedback at the shoulder or side of the trunk. Nevertheless, a greater reduction was observed compared to our results.

A further explanation for our smaller reductions might be the fact that subjects received less training and familiarization time in our study. Whereas either seven training trials [BCMS13], twelve practice trials (~15 minutes) [LKCS12] or a familiarization period of 20 minutes [WWSK01] were recently provided, in our study only the first trial with feedback was excluded from the analysis. Consequently, it is thinkable that our subjects were not that familiar with the feedback. Additionally, it might be that a single activated motor, which indicated that sway was exceeding thresholds in two directions, was hard to understand in the beginning.

When considering the amount of changes and percentage above threshold together, it seems that even though the amount of changes only slightly increased with feedback, subjects moved faster back below the threshold and remained longer within the borders.

6.1.2 COP

It was expected that feedback would decrease the RMS of sway. However, in our study feedback significantly increased RMS of COP (see section '5.2.2 RMS of Sway') and the SD of velocity (see section '5.2.2 SD of Velocity')of COP in ML and AP directions for narrow stance as well as for semitandem stance.

In the literature, there is evidence that IMU-based vibrotactile feedback to the upper body can reduce COP position parameters.
In contrast to our results, Kentala and colleagues [KVW03] showed a reduced COP displacement in AP directions as indicated by SOT5 and SOT6 which are tests to assess postural stability. The feedback was applied to the front and the back of the torso. Similarly to our work, they also assessed COP with a force plate and feedback was given based on an IMU placed at L2/L3 level in case angular displacement exceeded 1°. The major differences, however, between their and our study are the placement of the motors and the amount of directions in which feedback could be given. While they placed the motors at the lower torso, in our work they were placed at the upper torso. Furthermore, while Kentala et al. [KVW03] provided feedback in two directions (AP axis), we gave additionally feedback the ML axis and the diagonals, so in further six directions. Accordingly, since Kentala and colleagues [KVW03] only provided feedback in AP directions, sway was only reduced in this direction.
Similarly, the previously-mentioned device of Wall et al. [WWSK01] provided vibrotactile feedback only in one axis, however in ML directions. COP displacement was determined by a force plate. RMS of COP displacement in ML directions was significantly reduced with feedback compared to no feedback for shoulder and side tactors.
In the study of Janssen and colleagues [JSA+10] a similar configuration was used. Twelve motors were placed around the waist, whereas the sensor was either located at the head or the trunk. If body tilt exceeded 2° in one specific direction, the corresponding motor was activated. Consequently, feedback was provided in twelve directions. After a familiarization period of five minutes, participants practised for further 15 minutes with the system. Each condition was tested twice. The sway path of COP, which combines AP and ML sway, was measured by a force plate and decreased due to the feedback when the sensor was placed at the head. Over all subjects, no significant differences in sway path were found in case the sensor was located at the trunk. It needs to be considered that path length is not equal to the RMS. Even though both refer to the two-dimensional displacement, the RMS takes

greater deviations more into account [PN15].
The reduction was not only attributed to the feedback, but also to training, rising self-confidence and increased alertness of the patient. It was recommended to place the sensor at the head in patients with severe balance problems. However, apart from the quantitative results (decreased sway path) no explanations were given why this location might be superior [JSA+10].
According to Wall and colleagues [WWSK01] positioning the sensor at the head is advantageous in the sense of avoiding interferences between sensor and motors placed at the trunk. Additionally, they speculated that a decrease in head tilt is caused by a decrease in trunk tilt [WWSK01]. The review of Ghislieri et al. [GGP+19] stated that the most commonly used position to assess balance is the lower torso near L5. Additionally, movements at the head are often not linked to a loss of balance, as the head is often moved in everyday tasks, e.g. when having a look around and consequently hard to imagine as a reference for vibrotactile feedback in a general application.

In case vibrotactile feedback to the upper torso was coupled with the COP by force sensors attached to insoles, COP parameters (e.g. mean distance, RMS distance, ML and AP range) decreased when using feedback compared to no feedback [MWW+15]. Also in visual feedback, where the COP was represented in real-time, the SD of COP in ML and AP was reduced, whereas for COP velocity no changes occurred [JTL16]. This could give first indications to a possible necessity of an interconnection of the feedback with COP to decrease COP deviation. Nevertheless, there is evidence that COP parameters decreased when using feedback which was coupled to an IMU at the lower back [KVW03, JSA+10] or head [WWSK01, JSA+10]. The interplay is further discussed later in this chapter.

All these studies have in common that COP parameters were reduced when feedback was provided. However, there is also evidence that COP parameters might be differently influenced.
Comparably to our results, Lin and colleagues [LWL+15] reported a significantly greater RMS of COP in older adults when using feedback compared to no feedback during the first of two test days. In their study they placed both the IMU and the motors around the waist and additionally measured the COP trajectory by a dynamic posturography platform. They explicitly instructed subjects to move in the opposite direction of the vibration. Feedback was given based on angular displacements. In younger adults, who also participated in this study, no differences were found between feedback vs no feedback. The effect of an increased RMS of COP was only visible in older adults during their first of two test days. According to the authors, younger and older adults might have used different postural strategies [LWL+15]. They assumed that the increase in RMS of COP might have been caused by an increased use of hip strategy in older adults during the first of two test days. However, a hip strategy might have caused an increase in lower back tilt, which is opposite

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to what we observed. Furthermore, to explain this increase in RMS of COP, Lin et al. [LWL+15] suggested that vibrotactile feedback might have induced a perturbation and/or led to an overcorrection during the learning process (first test day) of older adults. This could give a hint that more training or familiarization would be needed to reduce COP position parameters.

The results of our user study indicated that the SD of velocity of COP was increased in ML and AP directions for both stances. Possible explanations for the increased SD of velocity were already given in the previous section for L5 (see section '6.1.1 L5'). Additionally, Warnica and colleagues [WWPL14] showed that higher levels of muscle activation in the ankle can lead to increases in COP parameters. Possibly, linked to the reactive response, muscle activity in the ankles and consequently body sway (both RMS and SD of velocity) might have been increased. The following paragraph aims to give further explanations for the discrepancy in results between L5 and COP.

6.1.3 L5 vs COP

It was expected that RMS of L5 and COP would be similarly influenced by feedback. This held true for the SD of velocity. Possible explanations for its increase were already given previously. However, for the RMS the pattern was contrary. With feedback, RMS was higher for COP, whereas it was smaller, according to the hypothesis, for L5. The following section aims to give further explanations for the discrepancy in results for L5 and COP.

First, it needs to be mentioned that only few literature investigated COP and upper body sway at the same time when evaluating vibrotactile feedback. To the best of our knowledge, only Wall et al. [WWSK01] simultaneously investigated COP and head tilt angle in the context of vibrotactile biofeedback with eyes closed. They demonstrated improvements for both COP and head tilt angle in terms of RMS. Even though Lin and colleagues [LWL+15] measured COP and trunk tilt, they did not present the results for the comparison feedback vs no feedback of trunk tilt.

The study of Lee et al. [LMS12] showed that COP metrics and trajectories measured by an IMU at L3 do not necessarily need to be consistent in the context of random vibrotactile stimulations, which were not coupled to the subject‘s body sway. They demonstrated that posture shifted in the direction of these stimulations and RMS of sway measured by an IMU was significantly higher during the vibrations compared to before and after, whereas no changes in COP metrics were detected.
Lin and colleagues [LWL+15] assumed for older adults that maybe hip strategy was used to a greater extent when receiving feedback at the waist, which led to an increased RMS of COP. The reason could be that the feedback induced perturbations, which were too strong to be compensated by the ankle [LWL+15].

The results of our study showed that even though changes in strategies (hip vs ankle) between both standing positions, semitandem stance and narrow stance with head in the neck, might have occurred, sway parameters of all standing positions tended to be equally influenced by the feedback. Additionally, as mentioned previously, hip strategy would probably increase the tilt angle at L5, which is contrary to our results.

Probably, receiving feedback increased the task difficulty, as subjects were not familiar with this type of feedback and consequently movement complexity [FRN13]. To handle the vibrations postural corrections by the upper trunk, the location of the vibrotactile feedback, might have induced an increase of COP, since COP is influenced by core movements, such as flexion and rotation [FRN13]. Additionally, it needs to be considered that the reference for vibrotactile feedback was located at the lower torso and consequently decoupled flexion or rotation movements of the upper torso might have rather influenced COP than L5 tilt angle.
Nevertheless, L5 measures (percentage above threshold and RMS) implied that corrective movements to reduce sway were executed by the subjects. Possibly, they were too extreme or led to a COP displacement, since the vibration could be stopped as soon as the orientation of the IMU was similar compared to the start of the trial, regardless of the position on the platform. Consequently, this fact could contribute to explain the discrepancies.
Lin et al. [LWL+15] also assumed that postural corrections by the trunk, which were larger with feedback compared to without feedback, induced larger changes of COP, contrarily to corrective movements by the ankle, and could consequently explain a worsening of COP measures.

Additionally, possible task-specific corrective, counteracting and precise movements to bring the COM position back into the dead zone when threshold was exceeded [BRT00] might have increased torques and thus COP deviations using a COM stabilization strategy, like it has been proposed by Morasso et al. [Mor20]. In this context, additionally, an increased awareness of the body position with respect to the reference/dead zone might have led to more frequent corrective movements around L5 (as indicated by the increased amount of changes at least in some conditions) within a small range of angular displacement [LKCS12], thus increased variability of velocity [KHG93]. Moreover, it has been shown that an internal focus increases total body sway in healthy young adults [CEY+18]. Another factor that might have influenced COP, additionally to core and ankle movements, is shifting body weight, which might have been used as part of the reaction strategy [FRN13].

Another possible explanation approach could be a kind of overcompensation. Eventually, subjects might have reacted too strong and received vibrational cues in the opposite direction while they were compensating previous feedback. E.g. after receiving cues at the front side the subject moved in (*attractive* or *no instruction* groups) or in the opposite direction (*repulsive* group) depending on the instruction group and consequently might have exceeded the other threshold so that vibrations

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were provided to the back side. Especially, subjects with low body sway thresholds might have faced this problem, as they had a smaller dead zone. Even though the discrepancy between RMS measured at L5 and of COP cannot be explained by this fact, it could also contribute to subjects increasing the COP displacement and less the angle at L5.

Previously, it was already mentioned that electrotactile and auditory feedback can positively influence postural control [VCP+08, DCH05, DHC07, CDC+05].
Electrotactile feedback applied to the tongue in all four directions (AP and ML) and referenced to head orientation reduced COP area and displacement in AP and ML directions [VPC+08]. When this type of feedback was coupled with a pressure mat, a decrease in SD of COP in ML and AP directions was observable in extended head position [VCP+08]. Additionally, there are some studies which investigated COP and trunk tilt at the same time for auditory biofeedback. Chiari et al. [CDC+05] found a reduction of COP displacement through auditory feedback in four directions and a high correlation between COP displacement and trunk acceleration.
Dozza and colleagues [DCH05, DHC07] showed similar results. RMS of COP and the acceleration at trunk level decreased due to auditory feedback, as indicated by different tones in AP and ML directions [DCH05, DHC07].
These findings give further evidence that vibrotactile feedback somehow might have induced perturbations, as it is directed to a certain body part, which can directly influence body sway, whereas auditory and electrotactile feedback give cues, which need to be further processed and translated from the ears or tongue into a response. Consequently, these types of feedback might support a similar response of COP and L5 trajectory. Even though this might indicate a superiority of auditory or electrotactile feedback against vibrotactile feedback, again, the disadvantages of those modalities, e.g. missed environmental cues [AEPY18, RMK+17] or the impossibility to talk and eat [VCP+08], need to be mentioned.
The results of Bechly et al. [BCMS13] also indicate a superiority of continuous visual feedback compared to vibrotactile feedback, as ML trunk tilt and variability decreased most with this type of feedback. However, tracking a moving target can induce dizziness and cannot be implemented in everyday life, as a display is required [BCMS13].

Furthermore, it has been shown that the type breathing could play a role, as thoracic breathing technique led to higher mean deviations of COP compared to abdominal breathing [HGL10]. Even though we did not assess the breathing technique higher COP displacements could be explained by this.

The above-mentioned explanation attempts could suggest that subjects were not moving the whole body 'en-bloc' and a coupling of the measuring devices (e.g. force plate and IMU at the lower torso) and the feedback is necessary to positively influence balance as a whole. Nevertheless, it remains unclear why some studies could show

an improvement in COP parameters, even though the feedback was linked to the lower torso [KVW03, JSA^{+}10] or head [WWSK01], and not the COP.
The devices of Kentala et al. [KVW03] and Wall and colleagues [WWSK01] only gave feedback in two directions. Possibly, this fact induced less 'perturbations' and did not induce weight shifts on the force plate. As a consequence, subjects improved their COP parameters. However, the previously mentioned study of Janssen and colleagues [JSA^{+}10] used even twelve motors and consequently could give feedback even in twelve directions and not just eight as in our study. Possibly, their configuration and placing the motors on the lower torso induced adaptations to the feedback of the body 'en-bloc' and the training period of 15 minutes might have led to a greater understanding of the feedback.

A last minor aspect to be mentioned, when fitting our results into current literature, is the vibration frequency of the motors. Recently, frequencies ranging from 200 Hz [LKCS12] to 300 Hz [JSA^{+}10] were used, with 250 Hz being the most common one [WWSK01, NMAP^{+}12, BCMS13, LWL^{+}15]. Our individually adapted intensities according to the vibration threshold were much lower (~100 Hz). From our results we cannot derive conclusion whether this fact might have negatively or positively influenced the outcome, as we did not compare our individually adapted frequency to fixed frequencies. However, the frequency range of Pacinian corpuscles is between 5 and 1000 Hz, where our frequency lays in, and our motor checks in the beginning of the user study guaranteed that subjects were perceiving the vibrations well. The following section compares our results with recent results of the phenomenon of light touch, which offers another possibility to positively influences posture.

6.1.4 Light Touch

Recently, several studies showed the beneficial effect of light touch (<1 N). E.g. Bonfim and colleagues [BGPB08] demonstrated that light touch decreased mean sway amplitude of COP in ML and AP directions during one-legged stance in healthy subjects and patients with anterior cruciate ligament injury.
Chen et al. [CT15] investigated the mechanisms of light touch. They found a significantly smaller SD of COP excursion of light touch compared to very light touch (<0.5 N). As indicated by the sensory hypothesis, higher-touch forces increase the number of sensory stimuli. Additionally, high precision, where subjects were instructed to keep the touch force near the middle of the range, also leads to higher postural stability compared to low precision, where subjects just needed to stay within the limits [CT15].
With vibrotactile feedback mainly only the sensory hypothesis can be influenced. We faced this by indicating the four major directions by two motors simultaneously. However, no conclusions can be drawn whether this was also more effective for vibrotactile feedback, as we did not compare our device with light touch. At least, this kind of feedback decreased the RMS of L5 sway.

In general, light touch and vibrotactile feedback follow a similar mechanism. They both provide additional information and augment perception [BFC+20].
Wall et al. [WWSK01] compared their shoulder and side tactors providing feedback in ML direction to light touch. They found that RMS of COP improved more with light touch with the finger compared to the vibrotactile devices. However, light touch was not reducing head tilt significantly. Additionally, the percentage above threshold was higher for light touch (~53 % (5 %)) compared to vibrotactile feedback at the side of the trunk and shoulders (~38 % (3 %)) even though it was reduced compared to no balance aids (~65 % (5 %)) [WWSK01]. In our study the percentage above threshold was reduced from ~43 % (25 %) to ~26 % (24 %) in the ML axis over all groups indicating that our feedback might be superior in decreasing the percentage above threshold compared to light touch (see Figure 5.9(a) and 5.10(a) for the results of the different groups). Wall et al. [WWSK01] concluded that (1) the sensed motion information, (2) the representation to the nervous system and (3) the usage of the information for balance are major factors that differentiate light touch from vibrotactile feedback. Whereas the vibrotactile device provided the subjects with additional information about head tilt, light touch gave reference to a fixed point. They concluded that it was logical that measures related to head movement, as RMS of head tilt and percentage above threshold, were more reduced by the vibrotactile feedback. [WWSK01]
This, again, supports the assumption that the reference device plays a major role in the effectiveness of feedback. Additionally, for clinical applications and everyday life situations, vibrotactile feedback seems to be easier to implement compared to light touch [BFC+20], as no stationary device or staff is required [RWLF01, JGGW09], and the vibrotactile devices are wearable.
This chapter discussed the influence of our vibrotactile feedback applied by the vest on human postural control. In the following, the influence of the different instruction groups is compared.

6.2 Influence of Group

Explanations for differences between feedback and no feedback were already given in the previous section. This section focuses on the differences which might have been induced by the type of instruction. To be able to see differences between groups, especially for the *no instruction* group, subjects were not provided with a familiarization phase.

For COP in all conditions and for all three groups at least tendencies existed for a higher RMS of sway and higher SD of velocity with feedback compared to no feedback, except for RMS in ML (semitandem stance) and SD of velocity in ML (narrow stance) in the *attractive* group, and RMS in AP (narrow stance) in the *repulsive* group (see section '5.2.2 RMS of Sway' and '5.2.2 SD of Velocity'). This indicates that subjects of all groups somehow responded to our vibrotactile feedback.

For L5 this pattern was different. In the *repulsive* group, RMS was significantly smaller in AP directions for both stances. Additionally, a tendency for smaller RMS existed for ML directions in narrow stance in the *attractive* and the *repulsive* group. Average values of the non-significant conditions also support the findings of smaller RMS values with feedback at L5 for the *attractive* and the *repulsive* group, being more pronounced in the *repulsive* group as indicated by the significance. In the *no instruction* group, RMS was barely influenced by feedback, especially in narrow stance. For semitandem stance, average values were slightly smaller with feedback (see section '5.2.1 RMS of Sway').
When solely considering the results of L5 which were coupled with the feedback and consequently connected with the stimuli, it seemed that subjects of the *attractive* and the *repulsive* group, with slight advantages for the *repulsive* group, were able to efficiently use the feedback given by the vest. Obtaining *no instruction* on how to move seemed to irritate subjects, and consequently, no clear benefit of the vest was found in this group as indicated by the RMS and the percentage above threshold. However, subjects of this group somehow responded to the vibrations, since RMS and the SD of velocity of COP were increased.
This could be due to the same reasons as mentioned before, such as shifting weight, increasing muscle activity and rotating or flexing the core. Though, in contrast to the other groups, there was less change in lower torso deviations, which might be due to no clear or different interpretations of the feedback. Additionally, as they obtained no clear instruction, they might have not completely understood how to use the feedback and consequently were not able to reduce the RMS of trunk tilt.
These observations were also confirmed by the ratings of QUESI. The intuitiveness was rated best in the *repulsive* group for *QUESI score* and all subitems, followed by the *attractive* group. Apart from *Subjective Mental Workload*, where the *attractive* group gave the lowest score, subjects of the *no instruction* group rated with the lowest scores. A possible explanation for the worse rating by the *attractive* group for *Subjective Mental Workload* could be that due to the received additional instructions compared to the *no instruction* group subjects needed to focus more on the feedback, which increased the workload. Statistical tendencies and significance for differences between the *repulsive* and the *no instruction* group for *QUESI score* and the subitems *Perceived Effort of Learning* and *Familiarity* confirmed these findings (see section '5.2.3 Intuitiveness of Group').

Comparably to the findings of COP, SD of velocity at L5 showed in all cases of the *attractive* and the *repulsive* group at least tendencies of being higher with feedback, except for ML in narrow stance (*attractive* group) and AP in narrow stance (*repulsive* group). For the *no instruction* group, only in ML direction for narrow stance a tendency existed (see section '5.2.1 SD of Velocity').

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Average values generally indicated a higher amount of changes between 'on' and 'off' when feedback was available. However, this was only supported in the *attractive* group by statistical testing. In all conditions, apart from AP directions in narrow stance, more changes occurred with feedback in this group. When going more into detail and considering the numbers, it became evident that the differences in the various groups between feedback and no feedback were approximately two changes at maximum, apart from the *attractive* group for semitandem stance in AP directions, where around five more changes occurred. Possibly, feedback did not only remind subjects to move back below the body sway threshold, but rather increased the consciousness of the subjects for their sway so that they stayed longer within their body sway threshold as indicated by the percentage above threshold. Consequently, the amount of changes just slightly increased with feedback, but this could also be caused by chance (see section '5.2.1 Amount of Changes').

The percentage above threshold is considered as another criterion for comparing feedback and no feedback. In the *attractive* and the *repulsive* group, this percentage was significantly lower in all conditions when feedback was available. This indicates that the feedback helped subjects to maintain the orientation of the IMU in narrower boundaries. In the *no instruction* group statistical testing revealed no differences between feedback and no feedback (see section '5.2.1 Percentage above Threshold').

The overall performance was not differing much between groups as the ANOVAs calculated for feedback and no feedback were not significant between the different types of instruction, apart from a tendency for RMS of L5 in AP directions with feedback between the *repulsive* and the *no instruction* groups.

In the previous chapter, the beneficial effect of several studies using repulsive feedback was already described [BCMS13, JSA+10, KVW03, LKCS12]. Additionally, Sienko and colleagues demonstrated that repulsive vibrotactile feedback was also efficient in reducing body sway and the percentage above threshold following perturbations [SBW12] and decreasing RMS trunk tilt in ML directions during challenging locomotor tasks [SBOW13]. Repulsive stimuli might incorporate the message 'here is something dangerous, move away'. In this sense, this kind of stimulus implementation has been used in navigation aids for avoiding obstacles [KAR18].

However, navigation belts are also used to indicate directions where to move to. Thereby, attractive stimuli are applied [AMS14]. Attractive stimuli not only have been used in navigation belts, but also in the context of biofeedback for postural control. For example, kinesthetic haptic feedback to the hand by a Phantom Omni® reduced mean velocity displacement, planar deviation and ML and AP trajectories [ABOY15]. Further, an attractive kinesthetic biofeedback to the trunk in ML directions reduced RMS of ML trunk tilt and acceleration [AEPY18]. Finally, subjects receiving no instruction moved intuitively in the direction of random vibrotactile

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stimuli applied to the trunk [LMS12]. However, in this study of Lee and colleagues, the stimuli were not coupled to the subject's sway.

Consequently, it is possible that the manner of encoding the message influences which type of feedback is more effective. In general, for vibrotactile feedback both options seem plausible. Either getting instructed in which direction tilt is needed or from where one should move away, latter e.g. representing an obstacle, which needs to be avoided. In a population of healthy young adults repulsive stimuli tend to be slightly superior compared to attractive stimuli in terms of objective measures (RMS of L5) and subjective feedback, as indicated by the QUESI. Instructions about how the feedback works seemed to be needed to increase the understanding and the performance.

6.3 Correlation COP and L5

To further investigate the relationship between COP and L5 patterns, correlations were calculated between their parameters. With this analysis it is aimed to contribute to the previously mentioned dissociation between L5 and COP (see section '6.1.3 L5 vs COP'). In six out of eight cases, Pearson correlation was higher without feedback compared to with feedback (apart for RMS in AP and SD of velocity in ML for narrow stance). Consequently, feedback seemed to influence the correlation between COP and L5 (see section '5.3 Correlation between COP and L5').

Overall, in AP directions correlations were small for RMS (0.066 - 0.244), whereas in ML directions they were moderate to strong (0.353 - 0.681). Consequently, there seemed to be different mechanisms in AP axis for COP and L5, independently of the availability of feedback, whereas they tended to be more connected in ML axis. This was contrary to our previous results of the effect of feedback, where the sway parameters (RMS of sway and SD of velocity) tended to be similarly influenced in both directions. Nevertheless, it could be that moving according to the vibrations just with the upper torso and mainly without changing the orientation of the IMU at L5 was more natural in AP compared to ML directions. This would have changed the position of COP and consequently might have decreased the correlation.
For the SD of velocity, mostly strong correlations existed between COP and L5. This was comparable to our previous results of the effect of feedback, as the SD of velocity of COP and L5 were both increasing and consequently showing a similar pattern with and without feedback. Nevertheless, correlations tended to be higher without feedback.

A mainly higher correlation for no feedback compared to feedback can be caused by the subject, who was actively reacting to the cues, whereas without feedback subjects acted unconsciously and more general with the whole body en-bloc. Generally, for

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no feedback this was in line with the current literature, which suggested a high correlation between COP and COM [WRM+11]. Whereas Whitney et al. [WRM+11] did not differentiate between AP and ML directions, Ekvall Hansson et al. [ET19] found high correlations in both ML and AP directions.
Additionally, the study of Chiari and colleagues [CDC+05] is amongst a few, which calculated the correlation of COP and trunk tilt for sway parameters, however, for auditory feedback. COP displacement and trunk acceleration, e.g. COP displacement RMS and acceleration RMS, were largely correlated ($0.7 < R < 0.9$). Previously, it was already supposed that auditory feedback might work differently in terms of the response by the subjects, as cues have to be transformed into movements. This assumption could also explain, why Chiari et al. [CDC+05] found such great correlations.

However, the state of research is not quite clear, e.g. Seimetz et al. [STKL12] suggested that different control mechanisms exist for IMU at trunk and COP. Additionally, Wall et al. [WWSK01] investigated the correlation between head tilt and COP and found no consistent pattern, as correlation coefficients were ranging from high-negative to high-positive.
Also in our study, patterns were not completely clear even though tendencies existed. However, this could indicate that overall each individual reacted differently to our feedback. Especially, as subjects were completely new in using such a feedback device.

6.4 Learning

As a secondary aim, we wanted to find out if over seven trials with either feedback or no feedback substantial learning or fatigue effects occurred. This was also one reason why we were not providing subjects with a familiarization period.
In general, it can be summarized that no learning occurred for feedback as well as no feedback for COP (see section '5.4.2 COP')and L5 (see section '5.4.1 L5'). The pattern was more or less random over all groups and conditions. This finding was supported by statistical testing, as nearly no main effect of trial became significant. The absence of significant results, apart from trial 2 and 6, where the SD of velocity of COP increased significantly over all groups for the condition without feedback in narrow stance in ML direction (Figure 5.24(b)), also indicates that fatigue did not play a role in this study.

First, it needs to be mentioned that only few studies investigated learning effects in the area of biofeedback.
Comparable to our results, Ballardini and colleagues [BFC+20] also found no learning effect for RMS of acceleration with feedback, even though they provided subjects with a familiarization period of 30 seconds.

After a training period of eight weeks an experimental group receiving vibrotactile feedback improved significantly more in balance and gait assessment tests compared to a control group, which was receiving no feedback. Testing was performed without feedback [BCK+18]. Even though this study did not investigate the learning effect of real-time feedback, it gives hints that using feedback over a longer period might positively influence balance.

A possibility why performance was not improving over seven trials could be that the feedback was intuitive enough that several trials did not affect the performance anymore. On the other hand, this could also have been caused by missing training with the device. In the work of Lin and colleagues [LWL+15], older adults did not reduce their COP displacement during the first visit, but during the second, which indicates that they needed additional training. Possibly, a training or familiarization period is needed to ensure that subjects completely understand the feedback and consequently improve over trials as usage becomes more natural and intuitive. Probably, even a familiarization period of 30 seconds as used by Ballardini et al. [BFC+20] was too short and the seven training trials provided by Bechly and colleagues [BCMS13] did not give subjects the opportunity to try out the feedback. Maybe just consciously allowing the subject to experience the feedback in all directions and the linkage with the IMU would be sufficient to enhance the understanding.
Furthermore, it could be that the task was complex and mentally demanding, as subjects needed to translate from where the feedback was given to where one had to move to counteract. Additionally, it needs to be considered that the adaptation time to such a device and its feedback is probably differing between subjects, with some individuals taking more time than others [LWL+15].

6.5 Correlation between Baseline Sway and Proportional Reduction

In this section the correlation between baseline sway and proportional reduction is discussed as is was expected that a higher amount of baseline sway would result in a greater reduction of sway parameters due to feedback. For RMS of sway, there was no overall pattern obvious. The SD of velocity showed a similar pattern in most of the parameters for COP and L5: positive correlations for the *attractive* and the *repulsive* group, no or negative correlations for the *no instruction* group. Positive correlations indicate that higher baseline RMS of tilt or SD of velocity go along with a higher proportional reduction due to the feedback (see section '5.5 Correlation between Baseline Sway and Proportional Reduction').
We assumed that higher baseline values go along with a higher reduction, which seemed to be supported by the results for the SD of velocity. However, it could also be that this pattern was random as for RMS. Possibly, subjects were too similar to be able to show a general pattern, as all have been healthy and young. A comparison

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with older subjects or patients with balance disorders could give further insights.

However, in the area of light touch there is already evidence that subjects with an ACL injury [BGPB08] or balance problems [BAAF14] especially take advantage of additional somatosensory information. For biofeedback, too, evidence exists that subjects with vestibular deficits [BCMS13, GBPP13] and older subjects [GBPP13] benefit more. Additionally, task difficulty seems to influence the results. In case some sensory input (e.g. visual information, foam surface) was not available, subjects improved to a greater extent [CDC+05, GBPP13]. The lack of information is substituted by the feedback [CDC+05].
On the other hand, Costantini et al. [CDC+05] found that younger subjects improved more when using auditory feedback compared to older individuals, as they had a higher reactivity to external feedback and responded quicker to multimedia stimuli.

We could not identify clear results for the correlations between baseline sway and proportional reduction. However, for further application, it is important to design a vibrotactile biofeedback device from which especially subjects with a low performance can benefit to a high extent as they are potential users of such a device. This is also the reason why this correlation was calculated.

6.6 Limitations

When interpreting the results of our study some limitations need to be considered. First, it needs to be mentioned that only young and healthy subjects were tested. This restricts the generalizability in comparison to older or diseased populations.

Furthermore, the alignment reset at the beginning of each trial could have influenced the data. This reset of the IMU was performed to zero the orientation. In general, this was done after subjects were instructed to stand still and they did not move anymore. However, sometimes subjects moved again or took a deep breath which could have changed their initial position. Consequently, the IMU might have been reset to an orientation which did not correspond to the normal baseline quiet standing position of the subject. Normally, the investigator observed such cases, terminated and repeated the trial. Nevertheless, there might be a few trials, in which it was not recognized and the trials were used for analysis. This fact could have pronounced the effect of the discrepancy in RMS between L5 and COP. Possibly, it would help to make subjects more attentive to this reset so that they additionally can even pay more attention to not conduct any movement at the beginning of the trial in the future. This fact also speaks in favour of conducting a familiarization period.

Probably, a familiarization period at the beginning of the experiment would have contributed to a better understanding of the vibrotactile feedback by all means.

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Possibly, our subjects did not completely understand the functioning of the vest, e.g. the diagonal feedback or overshoot with their response. Some studies mentioned that training is important to understand and use vibrotactile feedback [JSA+10] or navigation belts for visually impaired people [KAR18]. Consequently, training in general could help subjects to accommodate to the feedback and react more smoothly so that also a reduction in SD of velocity might get visible. Future studies should include a familiarization period.

Another aspect which needs to be mentioned, is the fact that our processor was not able to exhaust the full range of the DC motors. Voltage measurements indicated that the maximum frequency which we reached, corresponding to 100 % of motor intensity was at approximately 160 Hz as indicated by the product sheet. Determining the exact frequency fell below the scope of this study. However, we determined the motor intensity for each subject individually and the maximum intensities laid at around 50 % of motor intensity (corresponding to ~100 Hz), and consequently, our subjects did not need the full range of the motors to be able to sense the vibrations well. Additionally, even though the peak sensitivity of Ruffini corpuscles is around 200 Hz, their frequency range is from 5 to 1000 Hz [Joh02]. Consequently, even lower frequencies can be well perceived by humans and thus, this might not limit the validity of our results.

Lastly, it needs to be considered that we selected our formula for the body sway threshold for vibrotactile feedback on a small pilot study with six participants. Even though the choice for the formula was based on empirical data, we cannot guarantee that this is the best option.

6.7 Suggestions for Further Research

The area of vibrotactile feedback and our vest offer a broad range for further investigations. Several research ideas are described in the following.

In the current literature and also in this study, biofeedback was only based on either an inertial sensor, a force plate or pressure sensors, respectively. As our results showed that improvements were only visible for the reference device of the feedback, COP and COM reference devices could be combined. Ma and colleagues [ML17] already argued that a combination could be superior as both systems could compensate each other and consequently lead to improved sway parameters of COP and COM. It could be implemented by using separate body sway thresholds for COP and COM. As soon as one of them is exceeded, feedback is provided to the user.
Determining the body sway thresholds for biofeedback is not that straightforward [ML17]. As previously mentioned (see section '6.6 Limitations'), we based our body sway threshold for vibrotactile feedback on the findings of a small pilot study. There

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is no research if an individual body sway threshold, as used in this study, is superior compared to fixed thresholds, which are commonly used [LKCS12, WWSK01] even though the advantages seem apparent. Consequently, in further research it could be investigated on which variables the body sway threshold should be based on and whether it should be the same for all users or adapted to the individual baseline sway.
Furthermore, it could be investigated how frequent either one or two motors were active simultaneously in a follow-up study. Depending on these results, it might be thinkable to use a diamond or ellipse shaped dead zone instead of our rectangular shape, so that diagonal feedback is given earlier. Additionally, it would be interesting to assess in which direction subjects moved intuitively in respect to the stimulus, especially in the *no instruction* group. The behavior should be observed in a follow-up study.

Often motors were placed around the lower torso, whereas we located them at the upper body to shorten the processing time to the brain. The results of our study, however, suggested that subjects might react, especially, with their upper body to the feedback and not with their body as a whole. Consequently, it needs to be investigated whether a positioning at the lower torso provokes a more general response compared to a placing at the upper torso. Additional kinematic analysis might give insights about the used strategies (e.g. hip or ankle strategy, en-bloc or uncoupled upper-body movements).
Not only the location of the motors but also the number of motors needs to be considered. Following the sensory hypothesis we used at least for the major directions two motors to indicate one direction. However, it is not shown that this is superior to just using one motor. A tactor placing, as we used in our study could be compared to Ma et al. [MWW+15], who placed the motors at the anterior (the manubrium level), posterior (the first thoracic level), left (acromion) and right (acromion) side of the upper torso and consequently indicated directions by only one tactor.

This study is the first of our knowledge to investigate the effectiveness of the vest and further aspects need to be investigated to improve the device. Diagonal cues were only indicated by one motor even though sway was exceeding body sway thresholds in two directions. As those stimuli indicated severe deviations, it might be thinkable to increase the intensity of those cues to emphasize this fact. Another possibility might be to introduce a continuously increasing intensity based on the distance from the body sway threshold. The stronger the deviation is, the stronger the vibration becomes.

Previously, the phenomenon of Stochastic Resonance (SR) stimulation was already introduced (see section '2.2.6 Excursus: Stochastic Resonance Stimulation') which is mainly applied to the feet. However, it would be interesting to see if those sub-threshold stimulations to other body parts can also positively influence balance.

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Possibly, in further applications such a type of feedback could be used primarily for everyday use, whereby suprathreshold feedback as used in our study is taken for balance training.
However, it always needs to be kept in mind that feedback still needs to be simple and easy to understand.

For the application of the vest in everyday life it needs to be tested in different scenarios apart from quiet standing. First, the effects on dynamic balance or gait control could be investigated. Situations as climbing stairs or dual-task conditions are much more complex, but also more common in everyday life [MWL+16]. To ensure that subjects really understand the feedback a familiarization period should be included in further studies. Additionally, studies with pre-post design could give more insights in the effect of training.
Our results cannot conclusively confirm if repulsive or attractive stimuli are superior. This could also be tested further in different populations, as we only investigated young and healthy subjects. Additionally, performance differences could be investigated during long-term use.
As it is thinkable to use such a vest as a training device e.g. in rehabilitation, it might also be interesting to investigate the after-effects [BFC+20], and whether training with vibrotactile feedback can even lead to improved balance without wearing the device.

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Chapter 7

Conclusion

Through this research project the effectiveness and intuitiveness of a vest offering vibrotactile feedback to enhance balance were investigated. The vest is a low cost and portable device which provides vibrotactile stimulations according to an IMU placed at L5. In the following, the hypotheses are shortly confirmed and falsified, respectively. In general, it can be mentioned that both stances (narrow stance and semitandem stance) and directions (ML and AP) were similarly influenced.

> $\mathbf{H_0}$: Sway dependent vibrotactile directional feedback applied to the upper body does not positively influence postural control.

$$\mu_{\text{ Feedback}} \geq \mu_{\text{ No Feedback}}$$

The hypothesis can only be partially falsified. The results of the IMU indicated an improvement of balance by the feedback as indicated by a decreased RMS of tilt and a lower percentage above threshold, whereas the RMS of COP increased and consequently was worsened by the feedback. Additionally, feedback led to a higher SD of velocity for COP and L5, probably due to the response to the feedback.

> $\mathbf{H_0}$: The type of instruction (*attractive*, *repulsive* or *no instruction*) does not influence the effectiveness and intuitiveness on balance control.

$$\mu_{\text{ Attractive}} = \mu_{\text{ Repulsive}} = \mu_{\text{ No instruction}}$$

There tended to be an influence of group. Consequently, the hypothesis needs to be rejected. The RMS of tilt of L5 tended to be more reduced in the *repulsive* group compared to the *attractive* group. Additionally, the percentage above threshold was significantly decreased over all conditions in those two groups. However, in the *no instruction* group neither a beneficial nor a worsening effect of feedback was obvious. COP measures were similarly influenced over all three groups: a higher RMS of COP went along with a higher SD of velocity. The intuitiveness tended to be best rated in the *repulsive* group followed by the *attractive* group. The *no instruction* group was rated worst.

> $\mathbf{H_0}$: Vibrotactile feedback does not influence the correlation between COP and IMU (near COM) derived data.
> $$R_{\text{ Feedback}} = R_{\text{ No Feedback}}$$

Even though results were not completely conclusive, feedback tended to influence the relationship between COP and IMU as indicated by rather higher correlation coefficients in case no feedback was provided. Therefore, the hypothesis is falsified.

> $\mathbf{H_0}$: Seven trials of standing with and without feedback do not lead to a learning effect.
> $$\text{Feedback: } \mu_{\text{ trial1}} \leq \mu_{\text{ trial2}} \leq \ldots \leq \mu_{\text{ trial7}}$$
> $$\text{no Feedback: } \mu_{\text{ trial1}} \leq \mu_{\text{ trial2}} \leq \ldots \leq \mu_{\text{ trial7}}$$

The hypothesis is confirmed. No learning effect was obvious over seven trials, neither for COP nor for L5. The general absence of significance between trials additionally indicated that also no fatigue occurred.

> $\mathbf{H_0}$: There is no correlation R between baseline sway and the proportional reduction of sway due to biofeedback.
> $$R \leq 0$$

No general pattern was identified in this study. For RMS the correlation tended to be random, whereas for the SD of velocity, positive correlations for the *attractive* and the *repulsive* group, and no or negative correlations for the *no instruction* group were found. The hypothesis can neither be rejected nor supported.

In conclusion, our new approach providing real-time feedback by a vest in the main directions as well as the diagonals seems promising in reducing tilt at lower back, especially in the context that previous works showed a benefit only in the axis in which feedback was given in. However, instructions how to move are required. Repulsive cues indicating an obstacle avoidance seem to be slightly superior compared to attractive stimuli in terms of sway parameters as well as subjective feedback.
Additionally, our approach consisted of vibrotactile feedback which was adapted to the individual subjective sensation. Even though we did not investigate the effect of the individualized vibration frequencies compared to a fixed vibration frequency for all tactors, our approach ensured that 1) vibrations are well sensed, 2) front and back sides are of the same perceived strength and 3) the intensity is equally perceived by all users.
Vibrotactile feedback offers several advantages in comparison to other modalities. It can be easily worn in everyday life, even under clothes to consider aesthetic issues, and no display is required. Additionally, it is not distracting from other tasks, and therefore, it is very promising for improving balance and being able to prevent falls.

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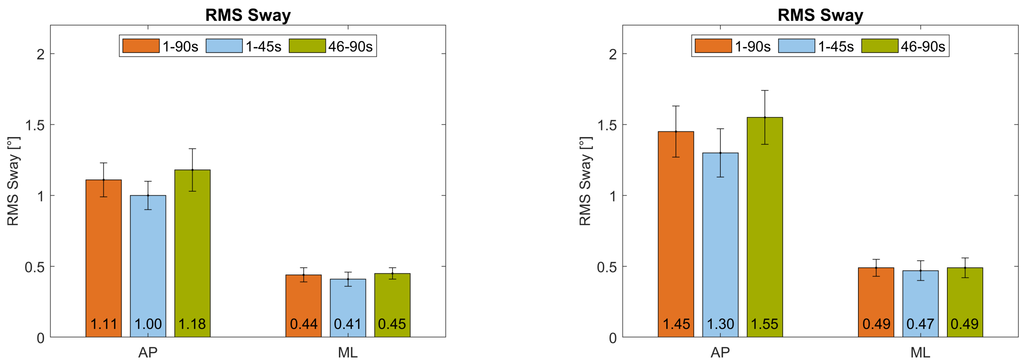
Appendix A

Appendix

A.1 Further Plots of the Pilot Study



(a) (b)

Figure A.1: RMS of sway for a) quiet standing and b) semitandem stance; error bars represent standard error of the mean; n = 6.

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A.2 Results of the Statistical Tests

Table A.1: Results of the mixed model ANOVA about the influences of feedback and group (L5).

Parameter	**Stance**	**Effect**	**F**	**p**	$\eta_p{}^2$
RMS in ML	NS	Feedback*Group	F(2,27) = 1.33	.282	.090
		Feedback	F(1,27) = 6.23	**.019**	.188
		Group	F(2,27) = 0.22	.806	.016
RMS in AP	NS	Feedback*Group	F(2,27) = 2.33	.116	.147
		Feedback	F(1,27) = 7.44	**.011**	.216
		Group	F(2,27) = 1.03	.371	.071
RMS in ML	ST	Feedback*Group	F(2,27) = 0.66	.523	.047
		Feedback	F(1,27) = 6.92	**.014**	.204
		Group	F(2,27) = 0.17	.843	.013
RMS in AP	ST	Feedback*Group	F(2,27) = 0.63	.540	.045
		Feedback	F(1,27) = 5.83	**.023**	.178
		Group	F(2,27) = 1.61	.218	.107
SD of Velocity in ML	NS	Feedback*Group	F(2,27) = 0.71	.501	.050
		Feedback	F(1,27) = 6.19	**.019**	.186
		Group	F(2,27) = 0.46	.638	.033
SD of Velocity in AP	NS	Feedback*Group	F(2,27) = 1.26	.299	.086
		Feedback	F(1,27) = 8.66	**.007**	.243
		Group	F(2,27) = 0.75	.480	.053
SD of Velocity in ML	ST	Feedback*Group	F(2,27) = 2.53	.099	.158
		Feedback	F(1,27) = 15.81	**.001**	.366
		Group	F(2,27) = 0.47	.630	.034
SD of Velocity in AP	ST	Feedback*Group	F(2,27) = 1.24	.305	.084
		Feedback	F(1,27) = 12.91	**.001**	.323
		Group	F(2,27) = 1.04	.366	.072
Amount of Changes in ML	NS	Feedback*Group	F(2,27) = 0.85	.437	.060
		Feedback	F(1,27) = 4.94	**.035**	.155
		Group	F(2,27) = 0.40	.672	.029
Amount of Changes in AP	NS	Feedback*Group	F(2,27) = 0.11	.896	.008
		Feedback	F(1,27) = 1.28	.269	.045
		Group	F(2,27) = 0.81	.456	.056
Amount of Changes in ML	ST	Feedback*Group	F(2,27) = 0.69	.511	.049
		Feedback	F(1,27) = 2.67	.114	.090
		Group	F(2,27) = 0.38	.686	.028
Amount of Changes in AP	ST	Feedback*Group	F(2,27) = 3.91	**.032**	.225
		Feedback	F(1,27) = 9.53	**.005**	.261
		Group	F(2,27) = 1.11	.344	.076

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Parameter	**Stance**	**Effect**	**F**	**p**	$\eta_p{}^2$
Percentage above Threshold in ML	NS	Feedback*Group	F(2,27) = 4.45	**.021**	.248
		Feedback	F(1,27) = 17.55	**<.001**	.394
		Group	F(2,27) = 0.39	.684	.028
Percentage above Threshold in AP	NS	Feedback*Group	F(2,27) = 3.19	.057	.191
		Feedback	F(1,27) = 20.84	**<.001**	.436
		Group	F(2,27) = 0.77	.475	.054
Percentage above Threshold in ML	ST	Feedback*Group	F(2,27) = 2.18	.132	.139
		Feedback	F(1,27) = 18.70	**<.001**	.409
		Group	F(2,27) = 1.28	.293	.087
Percentage above Threshold in AP	ST	Feedback*Group	F(2,27) = 1.40	.265	.094
		Feedback	F(1,27) = 15.01	**.001**	.357
		Group	F(2,27) = 0.44	.647	.032

Explanations: NS = narrow stance; ST = semitandem stance; significant results (p<.05) are indicated in bold.

Table A.2: Results of the univariate ANOVA about the influence of group (L5).

Parameter	**Condition**	**F**	**p**	$\eta_p{}^2$
RMS in ML	F_NS	F(2,27) = 0.04	.963	.003
	nF_NS	F(2,27) = 0.71	.499	.05
	F_ST	F(2,27) = 0.12	.888	.009
	nF_ST	F(2,27) = 0.40	.677	.028
RMS in AP	F_NS	F(2,27) = 3.42	**.047**	.202
	Rep vs nI		.074	
	nF_NS	F(2,27) = 0.65	.533	.046
	F_ST	F(2,27) = 1.55	.230	.103
	nF_ST	F(2,27) = 1.27	.298	.086
SD of Velocity in ML	F_NS	F(2,27) = 0.73	.493	.051
	nF_NS	F(2,27) = 0.07	.931	.005
	F_ST	F(2,27) = 1.61	.218	.107
	nF_ST	F(2,27) = 0.01	.988	.001
SD of Velocity in AP	F_NS	F(2,27) = 1.13	.338	.077
	nF_NS	F(2,27) = 0.46	.639	.033
	F_ST	F(2,27) = 1.33	.282	.089
	nF_ST	F(2,27) = 0.77	.472	.054
Amount of Changes in ML	F_NS	F(2,27) = 0.91	.414	.063
	nF_NS	F(2,27) = 0.06	.939	.005
	F_ST	F(2,27) = 0.60	.554	.043
	nF_ST	F(2,27) = 0.20	.823	.014

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Parameter	**Condition**	**F**	**p**	$\eta_p{}^2$
Amount of Changes in AP	F_NS	F(2,27) = 14.51	.452	.641
	nF_NS	F(2,27) = 0.93	.408	.064
	F_ST	F(2,27) = 2.41	.109	.151
	nF_ST	F(2,27) = 0.02	.979	.002
Percentage above Threshold in ML	F_NS	F(2,27) = 2.50	.101	.156
	nF_NS	F(2,27) = 0.08	.928	.006
	F_ST	F(2,27) = 2.42	.108	.152
	nF_ST	F(2,27) = 0.57	.572	.041
Percentage above Threshold in AP	F_NS	F(2,27) = 0.08	.922	.006
	nF_NS	F(2,27) = 2.20	.130	.140
	F_ST	F(2,27) = 0.07	.934	.005
	nF_ST	F(2,27) = 1.02	.375	.070

Explanations: F = feedback; nF = no feedback; NS = narrow stance; ST = semitandem stance; Rep = Group repulsive; nI = Group no instruction; significant results (p<.05) are indicated in bold.

Table A.3: Results of the dependent t-tests about the influence of feedback (L5).

Parameter	**Group**	**Stance**	**t**	**p**	$\mathbf{d_z}$
RMS in ML	Att	NS	t(9) = -1.84	.099	.581
		ST	t(9) = -1.77	.110	.562
	Rep	NS	t(9) = -1.98	.079	.626
		ST	t(9) = -1.73	.117	.549
	nI	NS	t(9) = -0.19	.851	.063
		ST	t(9) = -1.06	.317	.337
RMS in AP	Att	NS	t(9) = -1.72	.120	.543
		ST	t(9) = -1.65	.134	.520
	Rep	NS	t(9) = -2.78	**.021**	.879
		ST	t(9) = -2.25	.051	.710
	nI	NS	t(9) = 0.29	.780	.909
		ST	t(9) = -0.78	.455	.247
SD of Velocity in ML	Att	NS	t(9) = 1.43	.187	.452
		ST	t(9) = 3.33	**.009**	1.048
	Rep	NS	t(9) = 2.68	**.025**	.849
		ST	t(9) = 2.05	.071	.649
	nI	NS	t(9) = 1.94	.084	.614
		ST	t(9) = 1.07	.313	.340
SD of Velocity in AP	Att	NS	t(9) = 2.01	.076	.635
		ST	t(9) = 2.75	**.023**	.869
	Rep	NS	t(9) = 1.79	.107	.567
		ST	t(9) = 2.25	.051	.711
	nI	NS	t(9) = 1.55	.155	.494
		ST	t(9) = 1.06	.316	.337

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Parameter	**Group**	**Stance**	**t**	**p**	**d_z**
Amount of Changes in ML	Att	NS	t(9) = 2.46	**.036**	.779
		ST	t(9) = 2.08	.068	.657
	Rep	NS	t(9) = 1.06	.316	.336
		ST	t(9) = 1.21	.256	.383
	nI	NS	t(9) = 0.45	.665	.142
		ST	t(9) = 0.01	.990	.004
Amount of Changes in AP	Att	NS	t(9) = 0.81	.441	.255
		ST	t(9) = 3.02	**.014**	.957
	Rep	NS	t(9) = 0.36	.726	.114
		ST	t(9) = 1.46	.179	.461
	nI	NS	t(9) = 0.94	.370	.298
		ST	t(9) = 0.34	.744	.106
Percentage above Threshold in ML	Att	NS	t(9) = -2.76	**.022**	.870
		ST	t(9) = -4.19	**.002**	1.322
	Rep	NS	t(9) = -3.53	**.006**	1.116
		ST	t(9) = -3.11	**.013**	.980
	nI	NS	t(9) = -0.15	.887	.044
		ST	t(9) = -0.98	.353	.310
Percentage above Threshold in AP	Att	NS	t(9) = -3.42	**.008**	1.082
		ST	t(9) = -3.15	**.012**	.992
	Rep	NS	t(9) = -3.07	**.013**	.971
		ST	t(9) = -2.68	**.025**	.844
	nI	NS	t(9) = -0.91	.388	.284
		ST	t(9) = -1.05	.323	.333

Explanations: Att = Group attractive; Rep = Group repulsive; nI = Group no instruction; NS = narrow stance; ST = semitandem stance; significant results (p<.05) are indicated in bold.

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Table A.4: Results of the mixed model ANOVA about the influences of feedback and group (COP).

Parameter	**Stance**	**Effect**	**F**	**p**	$\eta_p{}^2$
RMS in ML	NS	Feedback*Group	F(2,27) = 0.13	.875	.010
		Feedback	F(1,27) = 10.90	**.003**	.288
		Group	F(2,27) = 0.20	.817	.015
RMS in AP	NS	Feedback*Group	F(2,27) = 0.49	.620	.035
		Feedback	F(1,27) = 14.28	**.001**	.346
		Group	F(2,27) = 0.21	.810	.015
RMS in ML	ST	Feedback*Group	F(2,27) = 0.50	.615	.035
		Feedback	F(1,27) = 26.84	**<.001**	.498
		Group	F(2,27) = 0.83	.449	.058
RMS in AP	ST	Feedback*Group	F(2,27) = 0.25	.779	.018
		Feedback	F(1,27) = 31.67	**<.001**	.540
		Group	F(2,27) = 0.16	.856	.011
SD of Velocity in ML	NS	Feedback*Group	F(2,27) = 0.25	.779	.018
		Feedback	F(1,27) = 31.67	**<.001**	.540
		Group	F(2,27) = 0.16	.856	.011
SD of Velocity in AP	NS	Feedback*Group	F(2,27) = 1.11	.343	.076
		Feedback	F(1,27) = 4.58	**<.001**	.600
		Group	F(2,27) = 0.23	.799	.016
SD of Velocity in ML	ST	Feedback*Group	F(2,27) = 2.81	.078	.172
		Feedback	F(1,27) = 38.44	**<.001**	.587
		Group	F(2,27) = 0.41	.669	.029
SD of Velocity in AP	ST	Feedback*Group	F(2,27) = 1.96	.160	.127
		Feedback	F(1,27) = 34.75	**<.001**	.563
		Group	F(2,27) = 0.10	.990	.001

Explanations: NS = narrow stance; ST = semitandem stance; significant results (p<.05) are indicated in bold.

Table A.5: Results of the univariate ANOVA about the influence of group (COP).

Parameter	**Condition**	**F**	**p**	η_p^2
RMS in ML	F_NS	F(2,27) = 0.13	.880	.009
	nF_NS	F(2,27) = 0.28	.755	.021
	F_ST	F(2,27) = 0.71	.502	.050
	nF_ST	F(2,27) = 0.83	.447	.058
RMS in AP	F_NS	F(2,27) = 0.002	.998	<.001
	nF_NS	F(2,27) = 1.04	.367	.071
	F_ST	F(2,27) = 0.09	.916	.007
	nF_ST	F(2,27) = 0.68	.517	.048
SD of Velocity in ML	F_NS	F(2,27) = 0.88	.427	.061
	nF_NS	F(2,27) = 0.97	.392	.067
	F_ST	F(2,27) = 1.15	.332	.078
	nF_ST	F(2,27) = 0.53	.593	.038
SD of Velocity in AP	F_NS	F(2,27) = 0.51	.607	.036
	nF_NS	F(2,27) = 0.12	.886	.009
	F_ST	F(2,27) = 0.44	.651	.031
	nF_ST	F(2,27) = 0.92	.411	.064

Explanations: F = feedback; nF = no feedback; NS = narrow stance; ST = semitandem stance.

Table A.6: Results of the dependent t-tests about the influence of feedback (COP).

Parameter	**Group**	**Stance**	**t**	**p**	$\mathbf{d_z}$
RMS in ML	Att	NS	t(9) = 1.66	.130	.528
		ST	t(9) = 4.28	**.002**	1.347
	Rep	NS	t(9) = 2.57	**.030**	.815
		ST	t(9) = 3.40	**.008**	1.071
	nI	NS	t(9) = 2.18	.057	.692
		ST	t(9) = 1.87	.095	.592
RMS in AP	Att	NS	t(9) = 2.57	**.030**	.813
		ST	t(9) = 5.63	**<.001**	1.777
	Rep	NS	t(9) = 1.40	.195	.443
		ST	t(9) = 3.23	**.010**	1.017
	nI	NS	t(9) = 2.56	**.030**	.810
		ST	t(9) = 2.21	.054	.700
SD of Velocity in ML	Att	NS	t(9) = 1.64	.136	1.024
		ST	t(9) = 4.93	**.001**	1.559
	Rep	NS	t(9) = 4.33	**.002**	1.369
		ST	t(9) = 3.48	**.007**	1.099
	nI	NS	t(9) = 2.24	.051	.708
		ST	t(9) = 2.14	.061	.675
SD of Velocity in AP	Att	NS	t(9) = 3.82	**.004**	1.209
		ST	t(9) = 4.59	**.001**	1.452
	Rep	NS	t(9) = 5.23	**.001**	1.653
		ST	t(9) = 3.78	**.004**	1.196
	nI	NS	t(9) = 2.68	**.025**	.844
		ST	t(9) = 1.93	.085	.612

Explanations: Att = Group attractive; Rep = Group repulsive; nI = Group no instruction; NS = narrow stance; ST = semitandem stance; significant results (p<.05) are indicated in bold.

Table A.7: Results of the mixed model ANOVA to investigate learning effects for feedback and no feedback (L5).

	Condition	**Effect**	**F**	**p**	$\eta_p{}^2$
RMS in ML	F_NS	Trial*Group	F(8.05,108.69) = 1.03 (GG.)	.419	.071
		Trial	F(4.02,108.69) = 0.73 (GG.)	572	.026
		Group	F(2,27) = 0.02	.979	.002
	nF_NS	Trial*Group	F(12,162) = 0.92	.528	.064
		Trial	F(6,162) = 0.39	.882	.014
		Group	F(2,27) = 0.59	.561	.042
	F_ST	Trial*Group	F(8.50,114.80) = 0.57 (GG.)	.811	.040
		Trial	F(4.25,114.80) = 0.70 (GG.)	.648	.025
		Group	F(2,27) = 0.09	.918	.006
	nF_ST	Trial*Group	F(3.90,52.70) = 0.50 (GG.)	.734	.036
		Trial	F(1.95,52.70) = 1.19 (GG.)	.312	.042
		Group	F(2,27) = 0.39	.682	.028
RMS in AP	F_NS	Trial*Group	F(8.52,115.07) = 1.04 (GG.)	.412	.072
		Trial	F(4.26,115.07) = 2.03 (GG.)	.091	.070
		Group	F(2,27) = 2.90	.072	.177
		Rep vs nI		.098	
	nF_NS	Trial*Group	F(8.35,112.78) = 0.94 (GG.)	.489	.065
		Trial	F(4.18,112.78) = 0.88 (GG.)	.482	.032
		Group	F(2,27) = 0.77	.475	.054
	F_ST	Trial*Group	F(12,162) = 1.66	.080	.110
		Trial	F(6,162) = 0.68	.664	.025
		Group	F(2,27) = 1.49	.243	.099
	nF_ST	Trial*Group	F(4.91,66.29) = 0.80 (GG.)	.553	.056
		Trial	F(2.46,66.29) = 1.56 (GG.)	.213	.055
		Group	F(2,27) =1.08	.352	.074
SD of Velocity in ML	F_NS	Trial*Group	F(5.97,80.59) = 1.08 (GG.)	.380	.074
		Trial	F(2.99,80.59) = 1.17 (GG.)	.328	.041
		Group	F(2,27) = 0.65	.528	.460
	nF_NS	Trial*Group	F(12,162) = 1.34	.200	.090
		Trial	F(6,162) = 3.53	**.003**	.166
		1 vs 3		.070	
		1 vs 6		.066	
		Group	F(2,27) = 0.10	.904	.007
	F_ST	Trial*Group	F(4.56,61.59) = 0.72 (GG.)	.596	.051
		Trial	F(2.81,61.59) = 1.15 (GG.)	.334	.041
		Group	F(2,27) = 1.82	.182	.119
	nF_ST	Trial*Group	F(12,162) = 0.89	.560	.062
		Trial	F(6,162) = 0.07	.999	.003
		Group	F(2,27) = 0.01	.993	.001

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	Condition	**Effect**	**F**	**p**	$\eta_p{}^2$
SD of Velocity in AP	F_NS	Trial*Group	F(8.41,113.52) = 1.55 (GG.)	.112	.103
		Trial	F(4.20,113.52) = 1.66 (GG.)	.161	.058
		Group	F(2,27) = 0.92	.413	.063
	nF_NS	Trial*Group	F(6.88,92.93) = 0.71 (GG.)	.659	.050
		Trial	F(3.44,92.93) = 1.92 (GG.)	.123	.066
		Group	F(2,27) = 0.53	.597	.037
	F_ST	Trial*Group	F(7.8,105.59) = 1.58 (GG.)	.103	.105
		Trial	F(3.91, 105.59) = 1.09 (GG.)	.373	.039
		Group	F(2,27) = 1.45	.252	.097
	nF_ST	Trial*Group	F(7.25,97.82) = 0.59 (GG.)	.845	.042
		Trial	F(3.62,97.82) = 0.67 (GG.)	.674	.024
		Group	F(2,27) = 0.77	.473	.054
Amount of Changes in ML	F_NS	Trial*Group	F(12,162) = 0.79	.664	.055
		Trial	F(6,162) = 0.88	.515	.031
		Group	F(2,27) = 0.91	.414	.063
	nF_NS	Trial*Group	F(12,162) = 0.88	.565	.061
		Trial	F(6,162) = 0.52	.794	.019
		Group	F(2,27) = 0.82	.922	.006
	F_ST	Trial*Group	F(7.02,94.84) = 0.46 (GG.)	.864	.033
		Trial	F(3.51,94.84) = 1.21 (GG.)	.305	.043
		Group	F(2,27) = 0.43	.656	.031
	nF_ST	Trial*Group	F(12,162) = 0.98	.473	.068
		Trial	F(6,162) = 0.77	.596	.028
		Group	F(2,27) = 0.04	.964	.003
Amount of Changes in AP	F_NS	Trial*Group	F(6.34,85.53) = 0.51 (GG.)	.811	.036
		Trial	F(3.17,85.53) = 1.18 (GG.)	.324	.042
		Group	F(2,27) = 0.28	.762	.020
	nF_NS	Trial*Group	F(7.34,99,10) = 0.45 (GG.)	.879	.032
		Trial	F(3.67,99,10) = 0.39 (GG.)	.885	.014
		Group	F(2,27) = 0.66	.527	.046
	F_ST	Trial*Group	F(8.39,113.23) = 1.20 (GG.)	.303	.082
		Trial	F(4.19,113.23) = 1.50 (GG.)	.206	.052
		Group	F(2,27) = 2.42	.108	.152
	nF_ST	Trial*Group	F(8.08,109.11) = 0.57 (GG.)	.806	.040
		Trial	F(4.04,109.11) = 0.69 (GG.)	.601	.025
		Group	F(2,27) = 0.05	.951	.004

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	Condition	**Effect**	**F**	**p**	$\eta_p{}^2$
Percentage above T in ML	F_NS	Trial*Group	F(8.52,115.02) = 1.42 (GG.)	.193	.085
		Trial	F(4.26,115.02) = 1.21 (GG.)	.309	.043
		Group	F(2,27) = 2.11	.141	.135
	nF_NS	Trial*Group	F(12,162) = 0.67	.779	.047
		Trial	F(6,162) = 1.28	.267	.045
		Group	F(2,27) = 0.05	.951	.004
	F_ST	Trial*Group	F(8.71,117.56) = 1.03 (GG.)	.420	.071
		Trial	F(4.35,117.56) = 0.84 (GG.)	.538	.030
		Group	F(2,27) = 2.42	.108	.152
	nF_ST	Trial*Group	F(12,162) = 0.81	.616	.057
		Trial	F(6,162) = 2.10	.056	.072
		Group	F(2,27) = 0.43	.658	.031
Percentage above T in AP	F_NS	Trial*Group	F(12,162) = 1.09 (GG.)	.377	.075
		Trial	F(6,162) = 0.59 (GG.)	.739	.021
		Group	F(2,17) = 0.05	.953	.004
	nF_NS	Trial*Group	F(12,162) = 0.88	.569	.061
		Trial	F(6,162) = 0.76	.603	.027
		Group	F(2,27) = 2.07	.146	.133
	F_ST	Trial*Group	F(12,162) = 0.62	.823	.044
		Trial	F(6,162) = 0.51	.803	.018
		Group	F(2,27) = 0.05	.956	.003
	nF_ST	Trial*Group	F(12,162) = 0.89	.556	.062
		Trial	F(6,162) = 0.42	.865	.015
		Group	F(2,27) = 1.05	.365	.072

Explanations: F = feedback; nF = no feedback; NS = narrow stance; ST = semi-tandem stance; Rep = Group repulsive; nI = Group no instruction; T = Threshold; significant results (p<.05) are indicated in bold.

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Table A.8: Results of the mixed model ANOVA to investigate learning effects for feedback and no feedback (COP).

	Condition	Effect	F	p	$\eta_p{}^2$
RMS in ML	F_NS	Trial*Group	F(12,162) = 0.79	.664	.055
		Trial	F(6,162) = 1.52	.174	.053
		Group	F(2,27) = 0.10	.905	.007
	nF_NS	Trial*Group	F(12,162) = 1.90	**.038**	.123
		Trial	F(6,162) = 1.31	.256	.046
		Group	F(2,27) = 0.45	.643	.032
	F_ST	Trial*Group	F(7.58,102.30) = 0.75 (GG.)	.638	.053
		Trial	F(3.79,102.30) = 1.13 (GG.)	.348	.040
		Group	F(2,27) = 0.84	.442	.059
	nF_ST	Trial*Group	F(7.87,106.27) = 1.30 (GG.)	.253	.088
		Trial	F(3.94,106.27) = 0.26 (GG.)	.898	.010
		Group	F(2,27) = 0.97	.391	.067
RMS in AP	F_NS	Trial*Group	F(5.96,80.45) = 1.27 (GG.)	.283	.086
		Trial	F(2.98,80.45) = 1.01 (GG.)	.419	.036
		Group	F(2,27) = 0.08	.919	.006
	nF_NS	Trial*Group	F(7.80,105.32) = 1.45 (GG.)	.187	.097
		Trial	F(3.90,105.32) = 1.57 (GG.)	.158	.055
		Group	F(2,27) = 0.86	.436	.060
	F_ST	Trial*Group	F(8.19,110.51) = 1.80 (GG.)	.082	.118
		Trial	F(4.09,110.51) = 0.69 (GG.)	.662	.025
		Group	F(2,27) = 0.10	.901	.008
	nF_ST	Trial*Group	F(12,162) = 1.91	**.036**	.124
		Trial	F(6,162) = 1.32	.250	.047
		Group	F(2,27) = 0.43	.656	.031
SD of Velocity in ML	F_NS	Trial*Group	F(5.84,78.90) = 0.57 (GG.)	.753	.040
		Trial	F(2.92,78.90) = 0.78 (GG.)	.507	.028
		Group	F(2,27) = 0.86	.435	.060
	nF_NS	Trial*Group	F(8.61,116.28) = 0.78 (GG.)	.628	.055
		Trial	F(4.31,116.28) = 4.26 (GG.)	**.001**	.136
		2 vs 6		**.019**	
		5 vs 6		.077	
		Group	F(2,27) = 1.05	.365	.072
	F_ST	Trial*Group	F(6.87,92.74) = 0.73 (GG.)	.648	.051
		Trial	F(3.44,92.74) = 2.15 (GG.)	.050	.074
		Group	F(2,27) = 1.15	.331	.070
	nF_ST	Trial*Group	F(8.90,120.16) = 0.41 (GG.)	.929	.029
		Trial	F(4.45,120.16) = 0.49 (GG.)	.762	.018
		Group	F(2,27) = 0.65	.530	.046

	Condition	**Effect**	**F**	**p**	$\eta_p{}^2$
SD of Velocity in AP	F_NS	Trial*Group	F(5.18,69.90) = 0.96 (GG.)	.448	.067
		Trial	F(2.59,69.90) = 1.71 (GG.)	.121	.060
		Group	F(2,27) = 0.57	.575	.040
	nF_NS	Trial*Group	F(7.92,106.87) = 1.26 (GG.)	.273	.085
		Trial	F(3.96,106.87) = 1.03 (GG.)	.408	.037
		Group	F(2,27) = 0.18	.834	.013
	F_ST	Trial*Group	F(6.06,81.84) = 1.11	.362	.076
		Trial	F(3.03,81.84) = 1.07	.384	.038
		Group	F(2,27) = 0.50	.614	.036
	nF_ST	Trial*Group	F(3.44,46.40) = 0.57	.661	.040
		Trial	F(1.72,46.40) = 0.51	.802	.018
		Group	F(2,27) = 0.95	.400	.066

Explanations: F = feedback; nF = no feedback; NS = narrow stance; ST = semitandem stance; significant results (p<.05) are indicated in bold.

Table A.9: Results of the univariate ANOVA to investigate the simple main effects of group for learning (COP).

Parameter	**Trial**	**F**	**p**	η^2
RMS in ML	nF_NS_1	F(2,27) = 2.23	.127	.142
	nF_NS_2	F(2,27) = 0.08	.924	.006
	nF_NS_3	F(2,27) = 0.60	.557	.042
	nF_NS_4	F(2,27) = 0.45	.644	.032
	nF_NS_5	F(2,27) = 2.04	.150	.131
	nF_NS_6	F(2,27) = 0.08	.922	.006
	nF_NS_7	F(2,27) = 1.00	.382	.069
RMS in AP	F_ST_1	F(2,27) = 0.60	.556	.043
	F_ST_2	F(2,27) = 0.13	.883	.009
	F_ST_3	F(2,27) = 1.97	.159	.127
	F_ST_4	F(2,27) = 0.68	.514	.048
	F_ST_5	F(2,27) = 0.19	.828	.014
	F_ST_6	F(2,27) = 1.51	.239	.101
	F_ST_7	F(2,27) = 2.17	.134	.138
RMS in AP	nF_ST_1	F(2,27) = 0.14	.869	.010
	nF_ST_2	F(2,27) = 0.41	.671	.029
	nF_ST_3	F(2,27) = 1.85	.176	.121
	nF_ST_4	F(2,27) = 0.12	.884	.009
	nF_ST_5 1 vs 2	F(2,27) = 3.11	.061 .071	.187
	nF_ST_6 2 vs 3	F(2,27) = 3.06	.063 .081	.185
	nF_ST_7	F(2,27) = 0.53	.597	.037

Explanations: F = feedback; nF = no feedback; NS = narrow stance; ST = semitandem stance.

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Table A.10: Results of the repeated measures ANOVA to investigate the simple main effects of trial (COP).

Parameter	**Group**	**F**	**p**	η^2
RMS in ML nF_NS	Att	F(6,54) = 1.22	.311	.119
	Rep	F(6,54) = 3.59	**.005**	.285
	1 vs 4		.052	
	4 vs 5		**.004**	
	nI	F(3.30,29.70) = 0.51 (GG.)	.799	.053
RMS in AP F_ST	Att	F(6,54) = 0.62	.717	.064
	Rep	F(2.19,19.67) = 2.10 (GG.)	.069	.189
	nI	F(6,54) = 0.66	.681	.068
RMS in AP nF_ST	Att	F(6,54) = 1.29	.277	.125
	Rep	F(6,54) = 1.47	.205	.141
	nI	F(6,54) = 2.64	**.026**	.227
	5 vs 6		**.026**	

Explanations: F = feedback; nF = no feedback; NS = narrow stance; ST = semi-tandem stance; Att = Group attractive; Rep = Group repulsive; nI = Group no instruction; significant results (p<.05) are indicated in bold.

A.3 Material for the User Study

Informed Consent

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Technische Universität München

Information for participants regarding the following study proposal:

„The Effect of Vibrotactile Biofeedback Applied by a Vest on Human Postural Control"

Dear Participant,

We are pleased about your interest into the above mentioned scientific study. In this document, we would like to inform you about the purpose and procedure of the study as well as the acquired participant's data. Please read the following document carefully and do not hesitate to ask any questions to the investigators. The experiment will take about **1.5 hours**. You are able to credit this time as research participation.

The participation in this study is entirely **voluntary** and you can withdraw your participation at any time regardless of any reasons, before, during and after the experiment (e.g. if you feel unwell). There are no disadvantages for your person.

You do not have to decide for your participation immediately. The following information aims at supporting you in your decision.

1. What is the aim of this study?

This study is necessary to investigate the influence of vibrotactile biofeedback on balance control. We want to get insights, how such a feedback needs to be designed in order to be as intuitive as possible. The goal of this research project is to develop adaptive robotic systems, which stabilize subjects with balance problems in their daily live.

2. What is the study's procedure and what do I have to pay attention to?

If you meet the study's requirements, your body size will be measured. Then, the vest and their motors are attached to your body. Additionally, an IMU is placed at your lower body to capture your body movements. First, we will determine your vibration threshold for the back motors. By pressing a button, you show that you can perceive or can no longer perceive the stimulus. Then, we will ask you to stand in different stances for 45 seconds with closed eyes. In some trials, you will receive feedback by the vest. After each trials, there is a short break. At any time, you can tell us, when you need a break. You are supervised during the whole experiment.

To ensure that you are standing safely and data collection takes place under optimal conditions, we would ask you to wear socks and tightly fitting (sport) clothes **(tightly fitting shirt).**

3. Which benefits do you earn from this study?

There are no immediate benefits for your person. Your participation and the study's results, however, contribute to the knowledge regarding a possible improvement of balance stability and the prevention of severe falls.

4. Which risks are associated with this study?

The risk associated with the experiment is not higher than during usual upright standing. There always remains a risk that you could lose your balance, which could lead to falls and injuries, in the worst-case bone fractures. In order to minimize this risk, we will do everything to prevent such cases and therefore, make sure that all unnecessary objects are removed, the floor is dry and that you have a physical support in case you lose your balance. For your protection, one examiner will constantly observe you and stand next or behind during all measurements. If any complications occur, we will stop the experiment immediately and provide first aid if necessary. Appropriate equipment is present, and an emergency call can be made at any time. The investigator will look after your well-being and provide breaks. Please inform the investigator if you feel uncomfortable. In this case we will interrupt the measurement or cancel it entirely.

5. Is there an insurance?

Due to the minimal risk associated with the experiment, there is no necessity for a particular insurance for the participant. During the experiment the study office's liability applies or your own medical insurance in case the accident was not caused by an employee of the university.

6. Who can participate in this study?

It is not possible to participate, if you cannot stand without personnel support with closed eyes for 45 seconds. If you are aware of any neurological, orthopedic or rheumatic diseases that limit you in standing quietly, you cannot participate. Furthermore, you cannot participate if you feel pain during standing or are not able to follow the investigators instructions. Furthermore, you should not be older than 35 years.

7. Who decides if you are excluded of this study?

You can withdraw from this study at any time, before, during and after the experiment. You face no disadvantages by your decision. Furthermore, the study's leader or investigator can decide to exclude you from the study or to cancel your participation prematurely, if this is necessary (e.g. in case of an accident).

8. What happens to your data?

During the experiments we will collect data about your person. This data is stored on electronic disks. The person in charge of the data handling in this study is Isabel Tannert (Isabel.tannert@tum.de) and Katrin Schulleri (Katrin.schulleri@tum.de). Processing of your data requires your written consent. Your data will solely be used for this study. This includes personal data like name and age as well as physical data. All identifying data will be pseudonymized, which prevents identification of your person by unauthorized parties.

The goal is to publish the study's results. Most articles are released on the university's and chair's website (https://www.hcr.ei.tum.de/home/).

Your personal data is saved by the Associate Professorship of Human-centered Assistive Robotics at the Technical University of Munich, Germany (Prof. Dr. Dongheui Lee, dhlee@tum.de). The data will be deleted after ten years/ expiration of legal term. Personal data as well as the pseudonym's mapping list, which allows to map data to your person, will be deleted after three years.

Consent to the processing of your personal data is voluntary. You can withdraw your consent at any time in the future without your prior consent's legitimacy according to Art. 6 § 1(a) GDPR being affected. After your withdrawal, we will immediately delete your personal data and pseudonym. Please address your inquiry to Isabel Tannert (Isabel.tannert@tum.de). After the deletion we will not be able to map your person to the experimental data and a withdrawal from the study itself is not possible anymore.

In compliance with legal requirements you have the right to information, restriction or deletion of your data and the right for your data to be transferred. The law allows you to submit a claim to the Bavarian Office for Data Protection.

Any questions regarding data protection and handling can be addressed to the Contact Person or the university’s Data Protection Office.

9. Whom can you refer to for further questions?

Please contact the Contact Person for further questions regarding the study’s content, requirements or procedure. The contact is listed on the first page of this document. For medical concerns you can contact your personal physician.

Technische Universität München

Consent to participation in the scientific study

„The Effect of Vibrotactile Biofeedback Applied by a Vest on Human Postural Control"

I was fully informed about the study's purpose, procedure, requirements and risks. I have carefully read the information document. I had the chance to ask any remaining questions and have understood the given answers and accept these. I am aware of the possible risks and benefits associated with this study.

I had enough time to consider my participation in this study and I am aware that my participation is voluntary. I was informed that I can withdraw from the participation at any time regardless of any reasons.

I know that my data will be pseudonymized and solely used for the purpose of this scientific study. I have received a copy of the information document and consent form in paper or digital form.

Hereby I agree that I voluntarily participate in this study.

____

Name of participant in block letters

____

Place, date and signature of participant

I have informed the participant about the study's purpose, procedure, requirements and risks and received the written consent by the participant or a legal guardian. I have made sure that the participant did understand all points and have resolved all remaining questions. In case of a participant being a minor, I have made clear that the study can be canceled at any time regardless of the legal guardian's consent by the study's investigators.

I ensure that I follow all ethical guidelines stated by the declaration of Helsinki.

__________________________________ __________________________________

Name of investigator | Signature of investigator

Questionnaire for Measuring the Subjective Consequences of Intuitive Use (QUESI)

QUESI

How do you rate the use of the haptic vest	Fully disagree	Mainly disagree	Neutral	Mainly agree	Fully agree
I could use the haptic vest without thinking about it.					
I achieved what I wanted to achieve with the haptic vest.					
The way the haptic vest worked was immediately clear to me.					
I could interact with the haptic vest in a way that seemed familiar to me.					
No problems occurred when I used the haptic vest.					
The haptic vest was not complicated to use.					
I was able to achieve my goals in the way I had imagined to.					
The haptic vest was easy to use from the start.					
It was always clear to me what I had to do to use the haptic vest.					
The process of using the haptic vest went smoothly.					
I barely had to concentrate on using the haptic vest.					
The haptic vest helped me to completely achieve my goals.					
How the haptic vest is used was clear to me straight away.					
I automatically did the right thing to achieve my goals.					

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Acronyms and Notations

ABF audiobiofeedback

ANOVA Analysis of Variance

AP anterior-posterior

BESTest Balance Evaluation Systems Test

BI Balance Index

BMI Body Mass Index

BLE Bluetooth Low Energy

CDP Computed Dynamic Posturography

COM Center of Mass

COG Center of Gravity

COP Center of Pressure

DC Direct Current

ERM Eccentric Rotating Mass

F Feedback

FCM Forced-Choice Method

GG. Greenhouse-Geisser-Correction

HF. Huynh-Feldt-Correction

IMU Inertial Measurement Unit

MIMIC Mobile Instrument for Motion Instruction and Correction

ML medio-lateral

MOL Method of Limits

MQTT MQ Telemetry Transport

nF no Feedback

PWM Pulse Width Modulation

QUESI Questionnaire for Measuring the Subjective Consequences of Intuitive Use

RMS Root Mean Square

SD Standard Deviation

SDK Software Development Kit

SOT Sensory Organization Test

SR Stochastic Resonance

WHO World Health Organization

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