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Immediate Effects of Vibrotactile Biofeedback Instructions on Human Postural Control

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Abstract— **Vibrotactile biofeedback can improve balance and consequently be helpful in fall prevention. However, it remains unclear how different types of stimulus presentations affect not only trunk tilt, but also Center of Pressure (CoP) displacements, and whether an instruction on how to move contributes to a better understanding of vibrotactile feedback.**

Based on lower back tilt angles (L5), we applied individualized multi-directional vibrotactile feedback to the upper torso by a haptic vest in 30 healthy young adults. Subjects were equally distributed to three instruction groups (*attractive* - move in the direction of feedback, *repulsive* - move in the opposite direction of feedback & *no instruction* - with attractive stimuli). We conducted four conditions with eyes closed (feedback on/off, Narrow Stance with head extended, Semi-Tandem stance), with seven trials of 45s each. For CoP and L5, we computed Root Mean Square (RMS) of position/angle and standard deviation (SD) of velocity, and for L5 additionally, the percentage in time above threshold. The analysis consisted of mixed model ANOVAs and t-tests (α-level: 0.05).

In the *attractive* and *repulsive* groups feedback significantly decreased the percentage above threshold ($p<0.05$). Feedback decreased RMS of L5, whereas RMS of CoP and SD of velocity in L5 and COP increased ($p<0.05$). Finally, an instruction on how to move contributed to a better understanding of the vibrotactile biofeedback.

I. Introduction

Falling can have serious consequences, as loss of autonomy, and even death in the worst-case. According to the World Health Organization (WHO) 28-35% of people aged 65 and older fall annually [1]. To improve balance in everyday life in people with postural instability, such as elderly or individuals with vestibular disorders [2], light wearable devices have shown to present a good solution. Visual, auditory, electrotactile or vibrotactile feedbacks give additional sensory information to improve balance [3]. Typically, such feedback devices provide cues about sway in case certain thresholds are exceeded, indicated e.g. by force sensors [4] or an Inertial Measurement Unit (IMU) [5]. Some studies have shown that this type of feedback can e.g. reduce Root Mean Square (RMS) of tilt angle [6] and Center of Pressure (CoP) [6], as well as percentage in time spent above threshold [7]. In contrast to the other mentioned modalities, vibrotactile biofeedback is unobtrusive, not distracting from other tasks [8] and not limiting other sensory organs (e.g. auditory or visual) [9]. Consequently, it is a promising approach in fall prevention for patients who do not require mechanical support [10].

Yet, many possibilities exist to design vibrotactile feedback devices. First of all, it can be applied to different locations [3] [11] [12]. Common locations that have been investigated are the torso and head [10]. Bao et al. [11] have investigated how the location of the stimulus influences the reaction time to vibrotactile feedback and found that providing the stimuli at the head showed shortest reaction times compared to the lower torso, finger, shank and foot in both healthy young and old adults. Nanhoe-Mahabier et al. [13] argued that the perception and processing of vibrotactile stimuli at the head are facilitated due to the closeness to the the cortical centres, which might be relevant in the elderly due to delayed neural transmission with increasing age. However, the application of feedback to the head is limited to situations without head movements, and thus is not suitable for everyday life. Additionally, Wall et al. [6] found that placing motors near the shoulder showed a slightly higher stabilizing effect compared to the sides of the trunk. Furthermore, most often feedback has been provided in the four cardinal directions (anterior, posterior, medial, lateral) [3], while improvements appeared mainly in the direction of stimulus, indicating a direction-specific control [9] [14].

Moreover, different ways of encoding information exist. Often, feedback was given in the direction of threshold exceeded. Thus, participants were instructed to move in the opposite direction of the stimulus (repulsive cue) [14]–[16]. On the other hand, in a few studies subjects were instructed to move in the same direction of the stimulus (attractive cue) during quiet standing [17] and during a triggered stepping task [18]. Moreover, it has been shown that posture shifts towards vibrations applied around the waist, if no instruction is given [19]. Lee and colleagues [20] attributed this to an improved proprioceptive internal representation and orientation. However, in those two latter studies feedback was not coupled to subjects' sway. According to a previous comparison of attractive and repulsive vibrotactile feedback at the lower back in healthy older adults [17] repulsive cues have led to more pronounced improvements compared to attractive stimuli. On the other hand, in an earlier study Asseman et al. [18] reported quicker reaction times for

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triggered stepping response, if the vibrotactile feedback on the head was provided in the same direction, which is why they chose an attractive feedback in their user study.

Most of the previously mentioned studies, including the study comparing attractive and repulsive cues [17], quantified balance performance only related to lower back movements and do not consider CoP. However, some studies recently have shown that CoP and the lower back do not necessarily show same effects [16]. Consequently, the question arises, how these two types of cuing (attractive and repulsive) affect not only trunk tilt, but also CoP displacements and whether instruction on how to move contributes to a better understanding of vibrotactile feedback.

Therefore, in this work 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 stimuli). We use attractive stimuli in the *no instruction* group, as recently subjects intuitively moved in the direction of random vibrations when no instruction was given [19] [20].

Since the previous comparison of attractive and repulsive feedback only observed effects on trunk tilt [17], we additionally assessed CoP as a measure of general postural stability [16] and the control variable of the Center of Mass (CoM) [21] [22]. Moreover, Kinnaird et al. [17] have provided attractive and repulsive vibrotactile feedback only in anterior-posterior direction. However, falling to the side has been reported as an important indicator for hip fractures [23], and the effect of vibrotactile biofeedback to be direction-specific [9] [14]. Therefore, we provided multi-directional feedback.

II. Methods

A. Haptic Device and its Feedback Specifications

For providing feedback in both cardinal, and non-cardinal directions with four motors, two motors are active simultaneously to indicate movements in the cardinal direction pairs (AP: anterior-posterior; ML: medial-lateral) (Fig. 1 right). If sway exceeds the dead zone (no feedback) in non-cardinal directions, only one motor is activated.

The device consists of four Eccentric Rotating Mass (ERM) vibration motors (10mm vibration motor 310-122; Precision Microdrives Inc.) with a lag time of 38ms and a rise time of 97ms. The motors are connected to a microcontroller (Beetle-ESP32, DFRobot) and powered by a lithium-polymer battery (Fig. 1 left). The front motors are attached beneath the clavicula at one-third of its length from the medial side and the back motors in the gap between spina scapulae and margo medialis of the shoulder blade.

Due to high inter-individual variability, Hirjakova et al. [16] recommended to individualize the vibration frequency. Consequently, to standardize the perception of vibration intensity, the vibration thresholds are determined for each subject individually. This procedure ensures that all subjects perceive vibrations with a similar intensity. The procedure is based on the Method Of Limits (MOL) approach [24]. The intensity of one motor is increased and decreased as long as the subject perceives and no longer perceives the stimulus, respectively. We repeat this procedure three times for each motor. The mean of the six obtained values is used as individual vibration thresholds of each motor location. With this procedure we ensure that 1) vibrations are well sensed, 2) front and back sides are of same perceived strength and 3) the intensity is equally perceived by all users.

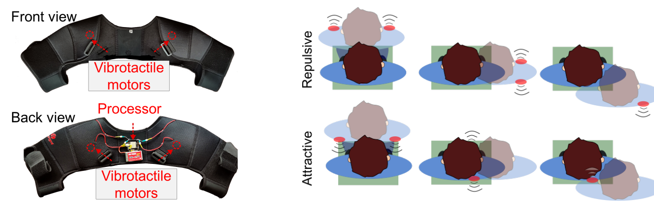


Fig. 1: (left) Haptic vest, fabric made with four ERM motors placed on the front and back side of the upper torso (front and back view); (right) exemplary representation of *attractive* and *repulsive* feedback: bird's eye view of person swaying, red ellipse = activated motors, green area = dead zone.

B. Measurement Devices

One IMU "MTw Awinda Wireless 3DOF Motion Tracker" (Xsens, Enschede, Netherlands) is placed at the lower back (L5) to measure tilt angles and accelerations. Tilt angles (Euler Angles) are used for providing vibrotactile feedback, as it has been reported that individuals relied more on feedback encoding sway angles compared to velocities [2]. A filter warm-up of 30s without moving the IMU is executed as recommended by the manufacturer [25]. Before each trial and as soon as the subject stands quietly, we conduct an alignment reset to set the orientation to zero.

To assess CoP displacement an AMTI force plate (Advanced Mechanical Technology, Inc., Watertown, MA) is used. We zero the force plate before each trial in an unloaded state. The sampling frequency is set to 100Hz for both IMU and force plate.

C. Pre-Study - Specifications for Vibrotactile Biofeedback

To identify differences of the vibration thresholds between the front and back of the upper torso, and accordingly determine a pleasant intensity of the vibrations, we conducted a pre-study with six participants (3 females, 3 males; mean age: 25.2 $\pm$ 1.0 years; average BMI: 21.5 $\pm$ 2.5kg/m^2). We determined the vibration thresholds and asked the subjects to rate suprathreshold vibration stimuli regarding how convenient/inconvenient they perceived the stimuli on a 7-level Likert scale to identify a pleasant, non-disturbing intensity. As it already has been observed in previous studies [26], differences in tactile sensation between back and front motors were visible, showing a lower sensitivity at the back, and thus a higher vibration threshold. Consequently, for the user study a motor intensity of 120% of average vibration threshold of the two back motors (VT_{back}) was used for the feedback applied by the front motors, whereas for the back it was set to 130%.

D. User Study - Evaluation of the Vibrotactile Biofeedback

To determine the influence of the haptic vest on L5 tilt and CoP displacement, as well as the importance of explicit instruction, we conducted a cross-sectional experimental study with 30 subjects. We recruited young adults in the age of 18-35 years in order to test the feasibility of the haptic vest. To ensure a well-fitting of the available haptic vest subjects were included having a Body Mass Index (BMI) of less than 30kg/m^2 and participants were asked to wear a tight and thin shirt. Moreover, participants were excluded if neurological, orthopaedic or rheumatic diseases were known, which could negatively affect standing with closed eyes. All subjects gave their informed consent and study execution followed the guidelines of the declaration of Helsinki. The study was approved by the ethics committee of TUM.

Following a short introduction, subjects were equipped with the devices and we assessed the vibration thresholds of the two back motors. Based on the mean (μ) of these vibration thresholds (VT_{back}) we determined the vibration intensity for the feedback, individually for each participant (front: 120% VT_{back}, back: 130% VT_{back}).

In a next step, we measured the baseline sway by three trials of quiet standing in a standardized Narrow Stance with feet 2.5cm apart and eyes closed (Fig. 2 left). These measurements were used to determine the body sway threshold ($1.2 * \mu_{\text{L5 tilt angle}}$) in AP and ML directions. If this threshold was exceeded in one or two directions during the feedback conditions, vibrotactile feedback of the corresponding motor(s) was activated as long as the subject exceeded the individual threshold (Fig. 1 right). On the other hand, as long as the subjects remained below the threshold no feedback was provided (dead zone) (Fig. 1 and 3).

Subjects were randomly assigned to one of three equal-sized groups (each n = 10, 5 females, 5 males):

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

Then, we tested four conditions: Semi-Tandem stance (ST) with and without feedback (Fig. 2 middle) as well as Narrow Stance (NS) with the head extended with and without feedback (Fig. 2 right). These two stances were chosen to induce an increased body sway once in AP directions by extending the head, which affects the vestibular system and increases postural instability [27], and once slightly more in ML directions by a Semi-Tandem stance [28]. Subjects were instructed to always stand upright and quietly with closed eyes in the marked position (2.5cm inter-heel distance [6]) on the force plate (Fig. 2). Arms were hanging on their sides. All subjects received the information that the vest provides vibrotactile feedback in some trials, which informs about their sway, and eventually further instructions according to their group affiliation.

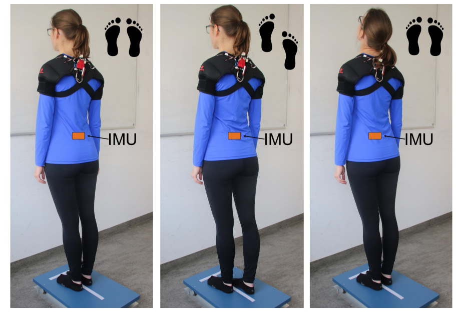


Fig. 2: Different stances: Narrow Stance (left), Semi-Tandem stance (middle), and Narrow Stance with head extended (right), with the placement of the haptic vest and the IMU, and marked foot placement on the force plate.

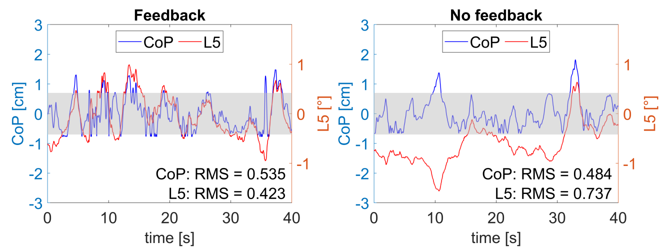


Fig. 3: Exemplary time course of the CoP and L5 trajectory with (left) and without feedback (right) for NS in ML (*attractive* group); grey area represents the dead zone.

The order of the conditions was block-randomized across subjects. One familiarization trial and six test trials were conducted for each condition with 30s rest between trials. Each order appeared once in each group to avoid order effects. Trial duration was set to 45s. In the end, subjects completed the Questionnaire for Measuring the Subjective Consequences of Intuitive Use (QUESI) to obtain subjective feedback about intuitiveness [29].

E. Data Analysis

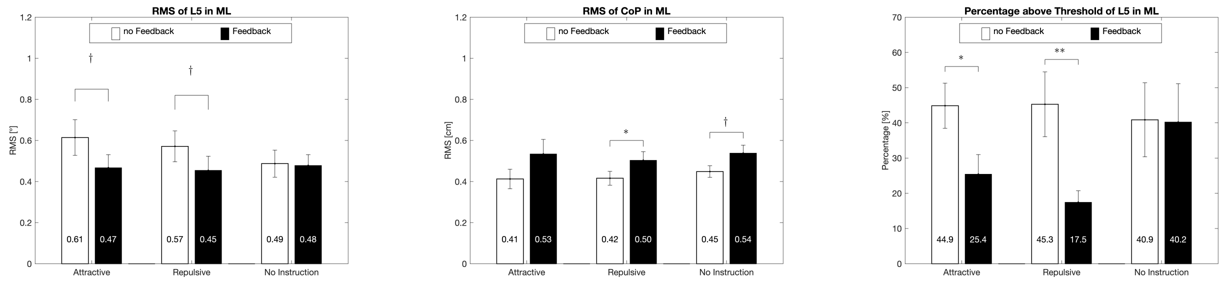
Data post-processing was performed using a MATLAB routine (MathWorks, Natick, MA). The first and last 2.5s were cut from each trial, so that 40s were used for analysis.

Parameters: RMS of body sway as well as the standard deviation (SD) of velocity were calculated for CoP and L5 data. For L5, additionally, the percentage in time the threshold was exceeded was determined (Fig. 3: white area). We calculated the parameters for each condition across trials.

Filtering: Force plate data were filtered with a zero-phase second-order Butterworth low-pass filter with a cut-off frequency of 10Hz. IMU data were already processed by the integrated Kalman filter [25].

Statistical Analysis: For the different sway parameters, a mixed model ANOVA was calculated. Differences between feedback and no feedback within each group were tested with dependent t-tests, separately for each stance condition.

The 14 items (5-level Likert scale) of the QUESI were assigned to the five subscales: *Subjective Mental Workload*,



(a) (b) (c)

Fig. 4: (a) - (c) Results of all parameters for ML directions of Narrow Stance; error bars represent the standard error of the mean; statistical significance indicated by †p<0.1, *p<0.05, **p<0.01, ***p<0.001; n = 30.

TABLE I: Proportional difference (%) of feedback vs. no feedback for the different parameters; signs indicate statistics of t-tests comparing feedback vs. no feedback in the different groups. Negative values indicate a reduction with feedback.

		Attractive (n = 10)		Repulsive (n = 10)		No instruction (n = 10)	
Parameter	Stance	AP	ML	AP	ML	AP	ML
L5: RMS	NS	−27.8	−23.0†	−43.4*	−21.1†	2.6	−2.0
L5: RMS	ST	−30.1	−31.4	−23.8†	−18.8	−10.5	−12.3
L5v: SD	NS	28.8†	30.5	16.0	17.9*	8.0	8.6†
L5v: SD	ST	26.1*	29.0**	21.6†	15.6†	8.4	4.8
L5: %	NS	−43.8**	−43.4*	−40.9*	−61.4**	−11.5	−1.7
L5: %	ST	−26.8*	−62.9**	−34.6*	−40.9*	−14.2	−17.9
CoP: RMS	NS	40.9*	29.3	17.5	19.0*	36.2*	20.0†
CoP: RMS	ST	56.0***	34.0**	41.1*	32.1**	38.9†	22.0†
CoPv: SD	NS	53.3**	51.8	42.4**	36.4**	29.1*	14.8†
CoPv: SD	ST	58.6**	39.3**	37.4**	26.6**	21.6	13.6†

*Explanations: v = velocity; % = percentage above threshold; NS = Narrow Stance; ST = Semi-Tandem stance; statistical tendencies and significance indicated by †p<0.1, *p<0.05, **p<0.01, ***p<0.001; n = 30; percentage difference (%) = $\mu\ ((_{feedback}$- $\mu_{no\ feedback})/\mu_{no\ feedback})$*100.*

Perceived Achievement of Goals, *Perceived Effort of Learning*, *Familiarity* and *Perceived Error Rate*. The *QUESI score* is the mean value over all items. High values indicate a higher probability of intuitive use. For the different subitems and the *QUESI score* a univariate ANOVA with Bonferroni post hoc tests was calculated across the different groups.

Normal distribution was tested with the Shapiro-Wilk test and QQ-plots were visually inspected. Levene test was used to test for homogeneity. However, according to Bortz [30], 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 in this study. For all statistical tests, α-level was set to 0.05.

III. Results

A. Subjects

All 30 subjects fulfilled the inclusion criteria. Subjects in the different groups were comparable in terms of their age (p = 0.075; 25.9 ± 2.9 years), BMI (p = 0.694; 23.1 ± 2.5 kg/m^2), VT_{back} (p = 0.136; 38.6 ± 3.2 %), vibration frequencies (front motors: p = 0.127, ~97 ± 7.7Hz; back motors: p = 0.139, ~105 ± 9.2Hz) and body sway threshold in AP (p = 0.524; 1.5 ± 1.0°) as well as in ML (p = 0.457; 0.6 ± 0.3°) directions.

B. Influences of Feedback and Group

1) Lower Back: The mixed model ANOVAs for L5 revealed a significant main effect of feedback for all three parameters (RMS of angle, SD of velocity, and percentage above threshold) in both stances (Semi-Tandem stance and Narrow Stance) and both directions (AP and ML). The availability of feedback led to decreased RMS of L5, smaller percentage above threshold and increased SD of velocity (for all p<0.05). Significant differences between feedback and no feedback solely occurred within the *attractive* and *repulsive* groups, especially for the percentage above threshold (Table I; Fig. 4 (a) & (c)).

2) Center of Pressure: For CoP a significant main effect of feedback for all conditions and parameters in both stances, in both directions as well as for both parameters (RMS of sway and SD of velocity) was observed, showing a significantly higher RMS of CoP (Fig. 4 (b)) as well as increased SD of CoP velocity with feedback (for all p<0.05). Significant differences between feedback and no feedback within groups mainly occurred for the *attractive* and *repulsive* groups and were more pronounced in Semi-Tandem condition (Table I). The time course of the L5 and CoP trajectory is exemplary shown for feedback as well as no feedback in Figure 3.

3) Intuitiveness of Use: For the overall *QUESI score*, the *repulsive* group tended (p = 0.077) to give higher ratings compared to the *no instruction* group; they showed higher ratings for the *Perceived Effort of Learning* (p = 0.040) and *Familiarity* (p = 0.066) (Fig. 5).

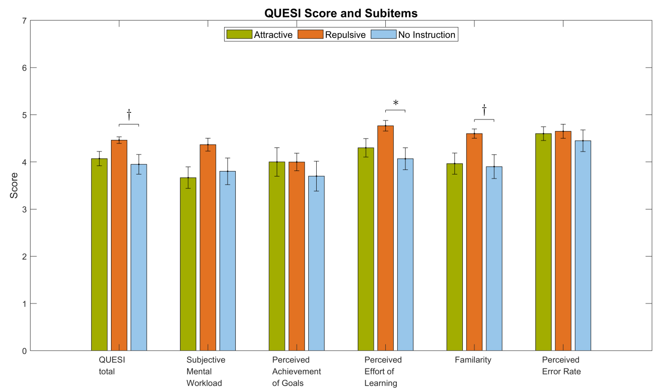


Fig. 5: QUESI results; error bars represent the standard error of the mean; statistical significance indicated by †p<0.1, *p<0.05, **p<0.01, ***p<0.001; n = 30.

IV. Discussion

This feasibility study aimed to investigate how different types of vibrotactile biofeedback cues applied by a haptic vest affect not only trunk tilt, but also Center of Pressure (CoP) displacements, and whether instructions are required. 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) in healthy young adults. To counteract the influence of inter-individual variability in perceptual sensitivity and ensure standardization, we individually adopted the intensity of the feedback. We expected the haptic vest to decrease sway parameter for L5 and CoP as well as differences between the different instruction groups.

A. Influences of Feedback

1) Lower Back: As expected, RMS of L5 decreased by vibrotactile feedback. These results go along with previous studies, as e.g. [6] [7] [9] [14] [16].

The increased SD of velocity could be explained by the voluntary response of the subjects to the stimuli, as we explicitly instructed the subjects to compensate the vibrations, which was comparably done in other studies [14] [31]. So, sudden reactions might have increased the variability in velocity together with smaller and more frequent postural corrections [9] [14] [16] (Fig. 3). This would indicate an increased voluntary postural effort [16].

Additionally, we could show a significant decrease in percentage in time threshold was exceeded, comparably as in other studies [6] [7] [14].

2) Center of Pressure: There is evidence that IMU-based vibrotactile feedback can decrease CoP displacement in AP directions when feedback is applied to the front and back of the lower torso (IMU at L2/L3 region) [5], in ML directions (RMS CoP) when tactors are attached to the sides of the subject [6], and overall RMS CoP when applied multi-directional around the waist in a sway referenced condition [31]. Contrarily to our expectations, CoP parameters (RMS CoP and SD CoP velocity) increased with feedback. Also Hirjaková et al. [16] observed a slight increase in RMS CoP in the elderly receiving feedback around the waist, though not significant. Moreover, Lin and colleagues [31] also found an increase in RMS of CoP in older adults during the first of two test days when standing on a fixed surface. Similarly to our study, feedback by a belt was referenced to an IMU at the waist and they explicitly instructed subjects to move in the opposite direction of the vibration. 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 increased trunk tilt, which is opposite than observed.

Possible explanations for an increased SD of velocity were already given in the previous section for the lower back. Additionally, linked to a reactive response muscle activity in the ankles and consequently body sway (both RMS and velocity) might have been increased [32].

The following paragraph aims to give further explanations for the discrepancy in results for CoP and L5.

3) Center of Pressure vs. Lower Back: Even though, Wall et al. [6] demonstrated improvements for both CoP and head tilt angle in terms of RMS due to a vibrotactile feedback, CoP was less reduced when feedback was given to the shoulders (17%) than to the sides of the trunk (33%), while head tilt was more reduced by feedback given to the shoulders (44%) than to the sides (35%). Two other studies providing vibrotactile feedback during quiet standing [16] and during postural perturbation [15] found similarly to us a dissociation of CoP and trunk measurements, though only with small effects during perturbation (ballistic phase). However, they did not observe a significant increase in CoP in young adults (firm surface, eyes open), but even observed simultaneous decrease in RMS L5 and CoP during a more challenging stance condition (foam surface) [16]. Besides weight shifting, postural corrections by the upper trunk might have induced larger changes of CoP in our study, since CoP is influenced by core movements, such as flexion and rotation [33]. Thus, possible task-specific corrective, counteracting movements to bring the CoM position back into the dead zone when threshold was exceeded [34], might have increased torques, and thus CoP deviations. Moreover, it has been shown that an internal focus increases CoP deviations in healthy young adults [35]. Thus, an increased awareness of the body position with respect to the reference or dead zone, might have led to more frequent corrective movements around L5 within a small range of angular displacement [14], thus increased variability of velocity [16] and CoP deviation, using a CoM stabilization strategy [22]. Consequently, L5 might have been stabilized by both the commonly known CoP stabilizing strategy (CoPS) [21] [22] where CoM is the controlled variable and CoP the control variable and the newly proposed CoM stabilizing strategy (CoMS) by Morasso [22] where CoP movements are constrained due to environmental conditions, and torques are caused by body shifts, such as the upper body or tools. Morasso [22] simulated the CoP trajectory and torques of a tightrope walker (with balance pole) by an inverted pendulum model with intermittent feedback control using the CoPS in sagittal (more stable) plane and CoMS in coronal (more challenging) plane. Since in our work stance conditions also had each a more unstable plane (NS with head extended: AP; ST: ML), it might be possible that upper torso movements counteracted destabilizing torques in the more unstable plane. By the additionally given biofeedback the counteracting movement might have been even more pronounced due to explicit instructions, thus resulted in higher torques.

Findings of simultaneous decrease of lower trunk tilt and CoP displacement by vibrotactile biofeedback applied by a belt [16] [31] further indicate more selected responses to vibrotactile feedback applied by a vest, as it is directed to certain body parts, which can be moved uncoupled from the rest of the body and directly influence body sway. This is also supported by the different amount of reductions depending on the feedback location found by Wall et al. [6]. Consequently, the relative location of sensor and feedback might influence the strength of the effect and coupling between CoM and CoP.

B. Influences of Instruction Groups

When solely considering the results of L5, which are coupled with the feedback, subjects of the *attractive* and *repulsive* groups, with slight advantages for the *repulsive* group, were able to efficiently use the feedback given by the haptic vest. The advantage of repulsive cues over attractive cues is supported by the results observed in elderly [17].

However, due to the previously reported faster reaction times in attractive cues (congruent stimulus-action coding) [18], and the lower-level skin stretch effect on body sway induced by vibration [20], the cognitive load [2] [10] [31] might be differently affected by these two encoding types. Moreover, a movement in the direction of the stimulus was only observed when the vibrotactile feedback was applied to the internal obliques, however, not when applied to the external obliques [20]. This might be due to different perceptual sensitivity dependent on the location, which influences the strength of postural response [20].

Obtaining *no instruction* on how to move, seems to irritate subjects and consequently no clear benefit of the vest was found in this group. However, subjects of this group somehow tended to respond to the vibrations, since RMS of CoP and SD of velocity of CoP were increased. This could be to the same reasons as mentioned before, such as shifting weight, increasing muscle activity and upper body movements. Though, in contrast to the other groups, there was less change in lower torso displacements, which might be due to no clear or different interpretations of the feedback.

These observations were also confirmed by the ratings of the QUESI. The intuitiveness, especially the *Familiarity* and the *Perceived Effort of Learning* subscales, were rated best in the *repulsive* group followed by the *attractive*, and the *no instruction* groups, which is also in line with the work of Kinnaird [17], in which elderly subjects reported to learn repulsive cues more quickly than attractive cues.

Consequently, in general, for vibrotactile biofeedback 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 and old adults, repulsive stimuli tend to be slightly superior compared to attractive stimuli in terms of objective measures (RMS) at trunk tilt and subjective feedback. Instructions about how the feedback works, seem to be needed to increase the understanding and the performance.

C. Limitations and Further Research

Possibly, our subjects did not completely understand the functioning of the haptic vest, or overshoot with their response. Consequently, familiarization 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. Because of previous research by Lee et al. [19] we did not include a fourth group (*no Instruction* with repulsive stimuli) and consequently cannot draw conclusions, whether attractive or repulsive cues are more intuitive in terms of subject's behavior. Therefore, the direction, in which subjects move intuitively with respect to the stimuli when no instruction is given should be observed in a follow-up study. In further research, the feedback could be additionally based on a combined reference of CoP and torso (see Hessfeld et al. [36]) and the intensity could continuously change depending on the degree of deviation to the body sway threshold, such as e.g. in [9]. In this work, we tested our approach in a restricted setup (closed eyes, head extended). Future studies should test it also in different populations and daily life related situations to address the target group more explicitly and to see if e.g. stimuli intensity and its characteristics need to be adapted. Finally, kinematic data are needed to understand, how subjects respond to the vibrotactile feedback in terms of strategies used, especially in a comparison of a feedback applied to the lower vs. upper torso and referenced to different sensor locations.

V. Conclusion

Our approach providing real-time feedback by a haptic vest to the upper torso in the cardinal and non-cardinal directions seems promising in reducing tilt at the lower back, however, it did not reduce underlying control effort of CoP, which might be due to the counteracting control movements of the upper body (CoM stabilizing strategy). Similarly as observed before in healthy older adults with vibrotactile feedback around the waist, 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. Moreover, instructions on how to move are required. Our approach consisted of vibrotactile feedback, which was adopted to the individual subjective perceptual sensitivity. 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 same perceived strength and 3) the intensity is equally perceived by all users. Our haptic vest could be useful for training balance-impaired patients, when the goal is to increase postural control effort while at the same time stabilizing CoM. For real-time feedback vibrotactile biofeedback applied by the haptic vest a longer training period to learn to maintain counteracting effort small might be required.

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