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Assessment of Balance Instability by Wearable Sensor Systems During Postural Transitions

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Abstract— **Several studies have demonstrated beneficial effects of real-time biofeedback for improving postural control. However, the application for daily activities, which also include postural transitions, is still limited. One crucial aspect is the time point of providing feedback, and thus its reliability. This might depend on the sensor system used, but also on how the threshold is defined. This study investigates which wearable sensor system and what kind of threshold is more reliable in a situation of a postural transition.**

To this end, we compared three sensor systems regarding their accuracy in timing in a stable and unstable postural transition in 16 healthy young adults: a multiple Inertial Measurement Unit system (*IMU*), a pressure Insoles System (*IS*), and a combination of both systems (*COMB*). Further, we contrasted two threshold parameters for each system: a Quiet Standing-based threshold (*QSth*) and a Limits of Stability-based threshold (*LoSth*).

Two-way repeated measures ANOVAs and Wilcoxon tests (α = 0.05) indicated highest accuracy in the *COMB LoSth*, though with small differences to the *IS LoSth*. The *LoSth* showed more accurate timing than the *QSth*, especially in medio-lateral direction for *IS* and *COMB*.

Consequently, for providing a reliable timing for a potential biofeedback applied by a wearable device in everyday life situations applications should focus on pressure insoles and a functional stability threshold, such as the LoS-based threshold.

I. INTRODUCTION

Falls are among the most common causes for injuries in the elderly and their prevalence is further increasing [1]. The main reasons for falls are gait and balance disorders resulting e.g. from a physical decline or neurological disease [1]. Consequently, researchers employ sensor technologies to objectively quantify balance disorders [2] and provide sensory feedback helping to improve patients' balance [2][3]. Besides stationary systems wearable devices have been developed. These devices are mostly based on Inertial Measurement Units (IMU) or a pressure Insoles System (IS) that estimate the patients' body motions [3]. A high variability in the Center of Mass (CoM) or Center of Pressure (CoP) trajectory indicate balance instabilities [3]. Once the CoM shifts outside the Base of Support (BoS), the body becomes unstable and there is a risk to tip over [4]. However, humans are able to cope with a certain degree of imbalance in order to prevent falls. A metric to quantify this ability are the so called Limits of Stability (LoS), the maximal displacement an individual can lean in any direction from an upright position without changing the BoS [5]. To measure static balance [6] and to provide biofeedback [3], often a single IMU is attached to the patient's lumbar area as an approximation of the CoM. However, such a single IMU is prone to detect unintended movements during postural transitions, such as Sit-to-Stand and vice versa [7], and thus, might trigger feedback in a situation in which the posture itself is stable. On the other hand, a biomechanical model based on a multiple IMU system can accurately estimate the CoM and ground reaction forces (GRFs) [8][9]. GRFs are commonly assessed by force plates or pressure insoles [3][6] to accurately analyze more dynamic situations such as gait [6], or for providing biofeedback in such situations [3]. However, e.g. in patients with orthopaedic insoles, pressure insoles might be not applicable [10]. Therefore, the question arises, if a multiple IMU system is comparable with a pressure insole system, or eventually a combination of both might be more accurate for triggering a potential feedback.

In the context of biofeedback for postural control, thresholds are often based on the deviation in the baseline sway (e.g. [11][3]) or a proportion of the voluntary LoS (e.g. [12]). The threshold's choice might influence the efficacy of the biofeedback given: Vibrotactile feedback reduced step reaction times in elderly in the work of Asseman et al. [13], however a work by Lee et al. [14] with an equal setup but different threshold definitions did not show reductions.

While previous works (see Review by Ma et al. [3]) have mainly focused on providing biofeedback for improving postural control during stance and gait, the application for daily activities, which also include postural transitions, is still limited [15]. For a biofeedback to be successful, it is crucial to define reliable criteria that indicate balance instability, and thus a reliable time point to give feedback. However, the accuracy in timing might depend on the sensor system used, but also on the threshold's definition.

Consequently, the aim of this work is to investigate which wearable sensor system and what kind of threshold is more reliable during postural transitions. Therefore, we compare three sensor systems with each other regarding their accuracy in timing in a stable (sPT) and unstable Postural Transition (uPT) in 16 healthy young adults: a multiple Inertial Measurement Unit system (*IMU*), a pressure Insoles System (*IS*), and a combination of both systems (*COMB*). Further, we contrast two threshold parameters for each system: a Quiet Standing-based threshold (*QSth*) and a Limits of Stability-based threshold (*LoSth*).

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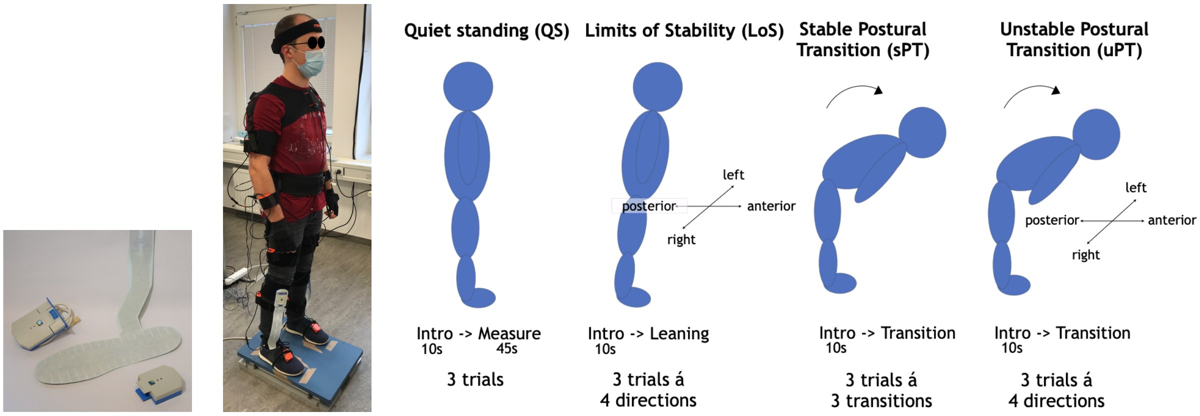

Fig. 1. Left: Medilogic insoles; Middle: Experimental setup - Participant standing in the initial upright position on a force plate with marked foot position, IMUs (orange boxes) attached via Velcro straps, and pressure insoles with wireless transmitter in the shoes; Right: Overview of the experimental procedure with two baseline measurements (QS & LoS) and two postural transition conditions (sPT & uPT).

II. METHODOLOGY

A. Subjects & Setup

16 (9 female) healthy athletic young adults (18-35 years, 1.73±0.1m, 64.5±8.98kg, BMI: 21.49±1.6kg/m^2) without any known medical history of neurological or musculoskeletal diseases participated in this study. Since the available measurement devices were restricted to a body height of 1.50 - 1.95m and a foot size of 23 - 29cm, participation was limited to individuals within these size ranges. The study was approved by the ethics committee of the Technical University of Munich. All participants gave written informed consent.

As the *IMU* we use the *Xsens MVN Link*, to track the CoM's position [9][16]. The *IS* consists of two wireless pressure insoles, based on which we calculate the CoP's position. Finally, a force plate (*AMTI HPS-SC*) functions as the reference system, measuring the CoP and the time point when the subjects alter their BoS (tipping point). All systems (Fig. 1) capture with a sampling frequency of 100Hz.

B. Experimental Procedure

The experiment comprised of four postural conditions (Fig. 1): two baseline (QS and LoS) and two postural transition (sPT and uPT) conditions. Each condition was conducted for three times. Within the LoS and the uPT each trial consisted of one transition for each direction. Within the sPT each trial consisted of three transitions. The order of the four conditions was same for all participants, each transition starting with a 10s *Intro* phase in which participants were asked to stand quietly in a hip-wide, upright position.

First, we asked the participants to stand as quietly as possible (QS) in the marked position with eyes open and straight gaze for 45s. We then carried out a four-way-leaning test similar to Thomson et al. [17], in which subjects were asked to lean in anterior, left, right and posterior direction separately as far as they could hold the outmost position (LoS) for 3s. In the sPT, participants were asked to bend over to 90° flexion at a given pace. In the uPT, subjects were asked to first bend over, like in the sPT, then lean in one direction, as in the LoS, however until they tip over.

C. Threshold Definition and Parameters

Based on the pressure insoles' and the IMU-system's output we computed the CoP [18] and CoM [16], respectively. Subsequently, the mean (μ) and standard deviations (SD, σ) across two trials of the detrended trajectories in mediolateral (ML, along x-axis) and anterior-posterior (AP, along y-axis) directions were used to compute the ellipse with the (co-)vertex of $(\mu - 2\sigma)/\sqrt{0.0077}$ and $(\mu + 2\sigma)/\sqrt{0.0077}$. The factor $\sqrt{0.0077}$ was based on the work of Johannson et al. [19], who found this factor to represent the relationship between the baseline sway area and LoS. The *LoSth* was defined by 90% of the four LoS values (AP, ML) [12], averaged across three trials. Consequently, we connected the four points in a standard ellipse to obtain the ellipse area of the *QSth* and the *LoSth*, respectively, for each system (Fig. 2).

We applied these thresholds to the data of the sPT's and the uPT's measurements and evaluated whether or at which time point the thresholds were exceeded. In the *COMB* system, the thresholds were exceeded as soon as the thresholds of both systems, the *IMU* and the *IS*, were exceeded. For the sPT, we computed the number of thresholds exceeded averaged across total number of transitions multiplied by 100 (proportional threshold exceeded (%)). For the uPT, we evaluated the time discrepancy (Δt) between the tipping point and the time point each system's threshold was exceeded. The tipping point was defined as the time point 20ms before the vertical force (F_z) falls below 85% of the subject's body weight. Shorter Δt indicate a more accurate and thus more reliable timing. The average of the three trials of each subject was used for statistical analysis.

D. Statistical Analysis

To assess differences between systems and thresholds, we computed a two-way repeated measures ANOVA following a 2x3 within subjects design with the factors 'Threshold' and 'System' and post-hoc paired t-tests for log-transformed Δt for uPT. Due to not normally distributed data of proportional threshold exceeded and violation of homoscedasticity, as well

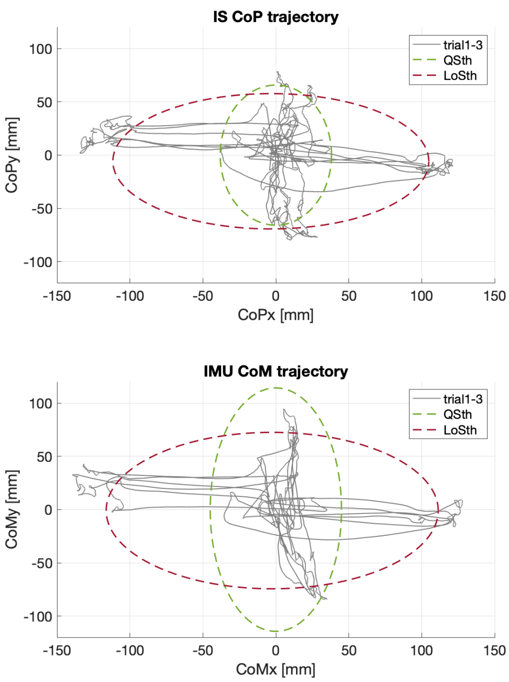

Fig. 2. CoM/CoP trajectories during the LoS measurements and the respective *QSth* and *LoSth* of each system.

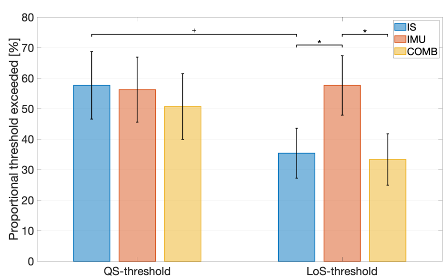

Fig. 3. Proportional threshold exceeded averaged across subjects; whiskers indicate Standard Error (SE), + = p<0.1, * = p<0.05, ** = p<0.01 .

as small sample size ($n = 16$), we computed Friedman and Wilcoxon tests in sPT. For the uPT, we evaluated the repeated measures ANOVA separately for each direction. Dunn-Sidak correction was applied for post-hoc comparisons. Data processing and statistical analysis were performed in *Matlab (v2020a)*.

III. RESULTS

A. Stable Postural Transition

The two-way Friedman test resulted only in a statistical tendency ($p = 0.06$). However, due to small sample size, we further computed post-hoc comparisons for the factors 'System' and 'Threshold'. One-way Friedman tests revealed a significant difference between systems only in the *LoSth* ($Chi^2(2) = 11.46, p = 0.00, n = 16$). Pairwise comparisons are shown in Figure 3.

B. Unstable Postural Transition

In all directions, thresholds were exceeded before reaching the tipping point, indicated by positive values. In anterior direction (Fig. 4, anterior), we obtained a significant main effect of 'System' ($F(2, 30) = 9.4, p = 0.00, \eta_p^2 = 0.39, f = 0.79$) and a significant interaction 'System x Threshold' ($F(2, 30) = 18.66, p = 0.00, \eta_p^2 = 0.55, f = 1.12$). Post-hoc pairwise comparisons resulted in a significantly shorter Δt for *IS* and *COMB* compared to *IMU* in the *LoSth*, as well as in a significantly shorter Δt for *COMB* compared to *IS* and *IMU* in the *QSth*.

In posterior direction (Fig. 4, posterior), we found a significant main effect of 'System' ($F(2, 30) = 11.49, p = 0.00, \eta_p^2 = 0.43, f = 0.88$), as well as a tendency for a main effect of 'Threshold' ($F(1, 30) = 4.43, p = 0.05, \eta_p^2 = 0.23, f = 0.54$) and interaction 'System x Threshold' ($F(2, 30) = 3.42, p = 0.06, \eta_p^2 = 0.19, f = 0.48$). Post-hoc tests revealed a significant difference of 1530ms between *IS* and *COMB* in the *QSth* and of 654ms in the *LoSth*, as well as a significantly shorter Δt for *IMU* compared to *IS* for the *QSth*. Regarding threshold effect, we observed a shorter Δt for the *IS LoSth*.

During the uPT left (Fig. 4, left), differences between the systems and thresholds were more distinct. We found a significant main effect of both 'System' ($F(2, 30) = 5.32, p = 0.02, \eta_p^2 = 0.26, f = 0.6$) and 'Threshold' ($F(1, 15) = 17.00, p = 0.00, \eta_p^2 = 0.53, f = 1.06$), but also a significant interaction 'System x Threshold' ($F(2, 30) = 11.35, p = 0.00, \eta_p^2 = 0.43, f = 0.87$). Post-hoc comparisons revealed in the *QSth* a significant difference between *IS* and *COMB*, with shorter Δt for *COMB* and a tendency for a difference between *IMU* and *COMB* in the *LoSth*. Further, a threshold's effect was significant for the *IS* and *COMB*.

Results of the uPT right (Fig. 4, right) were similar: There was a significant main effect of both 'System' ($F(2, 30) = 6.56, p = 0.02, \eta_p^2 = 0.3, f = 0.66$) and 'Threshold' ($F(1, 15) = 39.25, p = 0.00, \eta_p^2 = 0.72, f = 1.62$), as well as the interaction ($F(2, 30) = 10.14, p = 0.00, \eta_p^2 = 0.4, f = 0.82$). Within the *QSth*, the *IMU*'s and *COMB*'s Δt was significantly shorter than the *IS*'s, and within the *LoSth* there was a tendency for a shorter Δt for *COMB* compared to *IS* and *IMU*. Finally, regarding a threshold's effect, Δt of the *IS* and *COMB* was significantly shorter in the *LoSth* than in the *QSth* by 2326ms and 1613ms, respectively.

IV. DISCUSSION

This study aimed to investigate which wearable sensor system and what kind of threshold is more reliable during postural transitions.

A. Influence of Sensor Systems

In the sPT, differences between systems were dependent on the threshold parameters, since we could only observe differences for the *LoSth*. Thereby, *IS* and *COMB* showed highest reliability, due to a lower number of thresholds exceeded (Fig. 3). This coincides with results by El Achkar et al. [7] who report that an insoles-based system classifies postural transitions more accurately than a IMU-based system and detects less false positives.

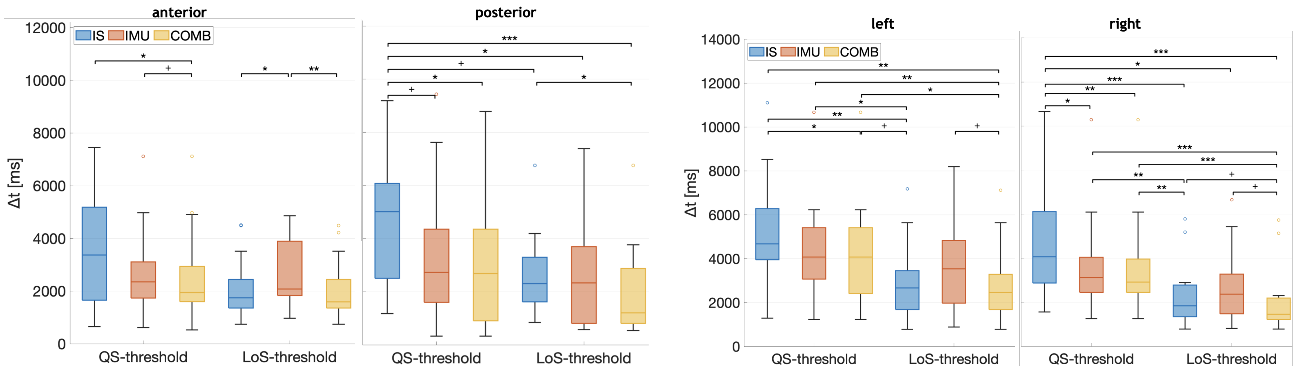

Fig. 4. Time discrepancy Δt between the tipping point and the time point of threshold exceeded during the uPT anterior & posterior and left & right across subjects; red line = median, whiskers = min/max, + = p<0.1, * = p<0.05, ** = p<0.01, *** = p<0.001 .

In the uPT, *COMB* consistently had shorter time discrepancies than the other systems, when the *LoSth* threshold was used. However, absolute differences were small between *COMB* and *IS*, but larger between *COMB* and *IMU*. Differences between *IS* and *IMU* were only significant within the *LoSth* in anterior direction. However, the trend shows that within the *LoSth* time discrepancy for *IS* was shorter and variation between subjects smaller (Fig. 4).

Average reaction times on vibrotactile stimuli lie around 500-600ms in a dual task setting and around 200-450ms without multi-tasking [20], depending on the age. In our best case, the *COMB LoSth*, the average time discrepancy was 1768ms (average across subjects and directions). This is four to five times higher compared to reported reaction times to both a surface perturbation [13][14] and to a vibrotactile stimulus [20]. Consequently, it might still trigger a potential biofeedback too early. However, in extreme cases, time discrepancy between threshold exceeded and the tipping point fell below 600ms, which might be too late for being able to respond in time, if being involved in another task. This high inter-individual variability of our results and the reported interpersonal variability in reaction times [21] and perceptual sensitivity [22], especially with increasing age, suggest that this needs to be considered when designing wearable devices for improving postural control in daily life.

As described in the introduction, we used a multiple IMU-system because previous studies showed that it more accurately estimates the body's CoM than a single IMU [8]. Moreover, an IMU-system reveals a good alternative for patients who cannot use pressure insoles [10]. However, the results of this work indicate that the *IS* and *COMB* were tendentially still more reliable with a *LoSth*.

B. Influence of Threshold Parameters

Considering differences between threshold parameters in the sPT, the *LoSth* tended to be more reliable for *IS* compared to the *QSth* (Fig. 3). In the uPT differences between systems and thresholds were more apparent in the ML direction (Fig. 4). The *LoSth* was more accurate than the *QSth*, especially for *IS* and *COMB*. Considering the different thresholds' definitions (Fig. 2), it can be observed that the *QSth* showed a more narrow threshold in ML direction compared to the *LoSth*, which was the case for most of the subjects. This can be attributed to a lower baseline sway in ML directions than in AP, due to the chosen hip-wide bipedal stance and due to the linear relationship with the baseline sway. However, previous studies have found that body sway increases with age [23], while the stability boundary (LoS) decreases [17][19][24]. Consequently, a tighter threshold would be needed with increasing sway for an elderly population. However, besides age, also other factors, such as anthropometry [25] influence our body sway. Respectively, it has been shown that body sway increases with body height and weight [25] which can be explained by the inverted pendulum model [4]. This increased body sway would not necessarily be related to an increased risk of falling, since functional LoS are also increased with anthropometry [23]. In case the age effect would be neglected, due to a study population of healthy young adults, as in our study, a wider *QSth*, thus, is appropriate when considering the influence of anthropometry.

On the other hand, the LoS have been reported to better consider the individuals' voluntary ability to control balance [5], and therefore might be more relevant in voluntary movements, such as bending over. Moreover, Johansson et al. [19] and Kilby et al. [24] pointed out the importance of the individual's LoS, when determining balance and risk of falling, and goes in line with the previously mentioned relationship of the range of motion and age [24]. However, assessing the real LoS in elderly might be limited, e.g. due to increased fear of falling, and thus might not represent the "real" stability limits [19]. Consequently, "comfortable" LoS measurements, which approach the real LoS, might be an alternative for the elderly. Instead of considering 90% of the LoS, as done in this study, for example, 110% of the "comfortable" LoS could be used.

Limitations and Future Research

Due to the higher inter-individual variability in the *QSth*, future studies should (1) include more than two trials in their analysis [17], which was the number of trials in our work (in QS) due to missing values in some of the three trials, and (2) normalize a baseline threshold [23][25] by known factors influencing body sway.

Moreover, the *QSth* definition was not optimal and did not fully reflect the participant's ability to voluntarily control balance in medio-lateral direction; the proportion factor between body sway during QS and the LoS might be not completely representative for our cohort because the subjects in [19] were older adults and showed smaller LoS than the ones we measured. Thus, future works should further investigate the relationship between QS and the LoS in different populations, such as in various disorders with disturbed postural stability and different age groups. Finally, the optimal time span a patient needs to react on the feedback signal should be further investigated under various daily situations and conditions.

V. CONCLUSIONS

The time point when feedback is given is crucial for a potential biofeedback to be successful and reliable. This work investigated how different wearable sensor systems and thresholds affect the accuracy in timing/triggering a potential biofeedback during a stable and unstable postural transition. A combination of a multiple IMU system and a pressure insoles system using a Limits of Stability-based threshold was most accurate in detecting postural instability. However, differences between the combined and insoles system were small and differences in performance threshold-dependent.

Future applications should focus on mobile plantar pressure systems, because the pressure insoles are less obtrusive and easier to integrate in everyday life than a combination with a multiple IMU system. Although, when considering the threshold used, a multiple IMU-system might still be an alternative for patients, who have to wear e.g. orthopaedic insoles which restricts the use of pressure insoles. Future works should approach a functional stability-based threshold, such as the LoS-based threshold. In the end, a prospective device would need to be tested in a cohort of older adults and different daily situations, other than the bipedal stance, to develop a reliable biofeedback system. In order to close the feedback loop, a real signal should be applied, such as investigated by Tannert et al. [11].

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