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Visual and proprioceptive contributions to postural control of upright stance in unilateral vestibulopathy

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Abstract

Preserving upright stance requires central integration of the sensory systems and appropriate motor output from the neuromuscular system to keep the centre of pressure (COP) within the base of support (BoS). Unilateral peripheral vestibular disorder (UPVD) causes diminished stance stability. The aim of this study was to determine the limits of stability and to examine the contribution of multiple sensory systems to upright standing in UPVD patients and healthy subjects. We hypothesised that closure of the eyes and Achilles tendon vibration during upright stance will augment the postural sway in UPVD patients more than in healthy subjects. Seventeen UPVD patients and 17 healthy subjects performed six tasks on a force plate: forwards and backwards leaning, to determine limits of stability, and upright standing with and without Achilles tendon vibration, each with eyes open and closed (with black out glasses). The COP displacement of the patients was significantly greater in the vibration tasks than the controls and came closer to the posterior BoS boundary than the controls in all tasks. Achilles tendon vibration lead to a distinctly more backward sway in both subject groups. Five of the patients could not complete the eyes closed with vibration task. Due to the greater reduction in stance stability when the proprioceptive, compared with the visual, sensory system was disturbed, we suggest that proprioception may be more important for maintaining upright stance than vision. UPVD patients, in particular, showed more difficulty in controlling postural stability in the posterior direction with visual and proprioceptive sensory disturbance.

Abbreviations

A_{dist}: The distance between the most anterior point of the COP during forward leaning and the anterior boundary of the base of support (the line connecting left and right metatarsal five)

COP: Centre of pressure

COP_{Amin}: The distance between the most anterior point of the COP_{Path} and the anterior boundary of the base of support (the line connecting left and right metatarsal five)

COP_{Path}: Total path length of the centre of pressure trajectory during 30s of quiet stance

COP_{Pmin}: The distance between the most posterior point of the COP_{Path} and the posterior boundary of the base of support (the line connecting the left and right heel)

corrected COP_{Amin}: The COP_{Amin} minus the A_{dist}

corrected COP_{Pmin}: The COP_{Pmin} minus the P_{dist}

EO: Eyes open: vision and proprioception uninhibited

EC: Eyes closed and black out glasses worn: vision inhibited

EOV: Eyes open with Achilles tendon vibration: proprioception inhibited

ECV: Eyes closed and black out glasses worn with Achilles tendon vibration: vision and proprioception inhibited

P_{dist}: The distance between the most posterior point of the COP during backward leaning and the posterior boundary of the base of support (the line connecting the left and right heel)

UPVD: Unilateral peripheral vestibular disorder

Introduction

The human ability to effectively control posture is the result of accurate function and interplay of the central nervous system and the musculoskeletal system. Due to continuous changes in the environment, functioning neurological and musculoskeletal systems and complex central integration of sensory input from the vestibular, visual and somatosensory systems are required to produce appropriate and safe motor task execution (Black et al. 1983, Peterka et al. 2002). In particular, the vestibular system, which generates vestibulo-ocular and vestibulospinal reflexes, plays an important role in this process. Impairment of the vestibular system can result in dizziness, loss of balance, or falls (McDonnell and Hillier 2015, Neuhauser et al. 2005, Walther et al. 2008).

During bipedal upright stance, healthy human subjects demonstrate relatively small movements of the centre of pressure (COP) in anteroposterior or mediolateral directions and are able to keep the COP within the limits of the base of support and hence, maintain upright standing without falling or taking an additional step (Di Fabio 1995, Mochizuki et al. 2006). The COP during quiet standing represents the position of resultant ground reaction forces under the feet and can be measured during static posturography using a force plate (Jonsson et al. 2004, Mochizuki et al. 2006). In order to examine postural control, disturbances of the sensory systems can be applied through visual (Pavlou et al. 2011), proprioceptive (Eklund 1972, Hytönen et al. 1989), or artificial vestibular (Peterka 2002) disturbance. Previous studies have demonstrated a decrease in stability during disturbance of visual input (Chien et al. 2014, Pavlou et al. 2011). Proprioceptive sensory input can be disturbed by vibrating the Achilles tendon (Eklund 1972, Hytönen et al. 1989, Spiliopoulou et al. 2012). Vibration applied to ankle flexor and extensor tendons results in an increased body sway during upright standing (Eklund 1972, Hytönen et al. 1989, Kanakis et al. 2014) and this response to tendon vibration increases with age (Abrahámová et al. 2009). This is due to activation of the muscle spindles during vibration, leading to muscle lengthening and thereby an increase in movement at the relative joint (Eklund 1972, Hytönen et al. 1989). The following correction of joint and segment position, reflected in an increased EMG activity of the ankle muscles (Spiliopoulou et al. 2012), is a result of segmental reflexes, supraspinal and central mechanisms involving the visual and vestibular systems (Eklund 1972). In this way, the contribution of each sensory system to static postural control can be estimated. Due to these processes and observed changes with different sensory disturbances, deficiencies in stability control during functional motor tasks could be expected if the vestibular, visual or somatosensory systems are dysfunctional and these sensory deficits have not been compensated for. A reweighting of sensory input may occur quickly and acutely in response to sensory disturbance (Eikema et al. 2014) or chronically to compensate for persistent dysfunction of one system (Allum and Adkin 2003), and in some cases, compensation may not be complete. Therefore, static posturography represents a tool in order to objectivise dysfunction and compensation of the sensory systems due to conditions such as vestibulopathy (Corriveau et al. 2001, Di Fabio 1995).

Various causes such as infection, trauma or circulatory disturbance may affect the function of the vestibular system (McDonnell and Hillier 2015). One of the most common causes of vestibulopathy are unilateral peripheral vestibular disorders (UPVD) that can cause vertigo, imbalance and falls (McDonnell and Hillier 2015, Neuhauser et al. 2005, Walther et al. 2008). Previous studies have demonstrated negatively affected upper and lower body motor control during standing, sitting and perturbed walking in patients with UPVD (Borello-France et al. 1999, McCrum et al. 2014, Raptis et al. 2007). Due to the stability and motor control issues seen in UPVD, posturography under different sensory disturbances represents a potential method to analyse postural control and sensory compensation in these patients. By systematically challenging or perturbing the visual and somatosensory systems, it could be possible to determine which contributes more to upright standing balance control in patients with vestibulopathy (Peterka et al. 2011). Therefore, it may be possible to determine which system plays a more important role in sensory reweighting in specific patient groups.

For this study, we recruited patients with UPVD due to vestibular neuritis. Our aim was to examine the contribution of the visual and proprioceptive systems to standing postural control with the absence of visual sensory input through closure of the eyes and black out glasses, and vibration of the Achilles tendon in UPVD patients and healthy control subjects. We chose to use Achilles tendon vibration as opposed to an unstable surface, such as a foam mat, to ensure that the mechanoreceptors in the soles of the feet were exposed to the same conditions in each task. In addition, Achilles tendon vibration may lead to a substantial effect on postural control and orientation, and the stimulation of the triceps surae muscle spindles may affect the perception of the vertical position of the body (Thompson et al. 2007), especially when the visual and vestibular perception of vertical orientation is perturbed. It was hypothesized that the absence of visual information and disturbance of the proprioceptive systems would increase the postural sway in patients with UPVD to a greater extent than in healthy subjects, thereby revealing reduced balance maintenance ability in the patients. Such findings could enhance our understanding of the role of the visual system and the triceps surae muscle spindles in postural control during functional motor tasks in vestibulopathy patients, as knowledge of the compensation of the sensory systems in such patients may aid in the design of rehabilitative programmes to encourage such compensation.

Materials and Methods

Subjects

17 adults suffering from UPVD for more than 6 months (10 females, 7 males, mean age: 49 years (SD 9); body height: 171.4 cm (SD 7.3); body mass: 73.8 kg (SD 14.1)) and 17 healthy adults (10 females, 7 males mean age: 51 years (SD 8); body height: 172.5 cm (SD 8.2); body mass: 75.1 kg (SD 15.2)) participated in the study. Independent t-tests revealed that the

groups were not significantly different in age, height, or body mass ($P > 0.05$). Vestibulopathy was confirmed by an ear, nose and throat specialist with a review of patient history and a clinical examination for spontaneous and induced vestibular nystagmus, bithermal caloric tests under videonystagmography, head impulse tests, rotating chair tests and the examination of balance and coordination using straight line walking, Romberg (standing balance) and Unterberger (stepping in place in a dark room to examine for rotation to the affected side; Zamyslowska-Szmytke et al. 2015) tests. All patients suffered from uncompensated unilateral vestibulopathy due to viral infection-induced vestibular neuritis. Vestibular deficits on the right side were found in fifteen of the patients and deficits on the left side were found in two. Spontaneous nystagmus was detected in one patient, with five showing positive results for head-shaking nystagmus. Sixteen failed the Unterberger test, demonstrating a pathologic rotation during stepping in place to the affected side, 12 failed the test of straight line walking with eyes closed, nine showed deficits in the head impulse tests. All patients reported rotational vertigo and eight of them suffered from instability and unsteadiness. Four patients had fallen in the previous six months (all at home, three on staircases), not resulting in serious injuries. The healthy subjects participated in identical examinations and tests, conducted by the same ENT-specialist, to make sure they did not suffer from any peripheral vestibular disorder. No form of nystagmus and no balance or coordination problems were identified. Only one control subject failed the Unterberger test, but this was attributed to a lack of concentration. As the subject didn't show any other indications or symptoms of UPVD, the subject was not excluded from the study. Further inclusion criteria for the subjects were no participation in physical exercise more than once per week and no other health problems that could influence postural balance. The experimental procedures for the study were explained to the subjects and written informed consent was obtained prior to the testing, following the guidelines of the ethical board of the German Sport University Cologne.

Postural sway analysis during different task conditions

Postural stability was investigated by means of static posturography. Displacements of the COP in the anteroposterior and mediolateral directions were assessed by a custom made force plate embedded with strain gauge force sensors, recorded with a sampling frequency of 1000 Hz and analogue-digital conversion to a computer. During the examination, all subjects stood barefoot on the force platform, with their feet parallel at pelvic width and with the heels on a marked line on the force platform. Subjects always wore a safety harness connected to an overhead track. For each subject, the initial positions of both feet on the plate were marked in order to transform the coordinates of the anterior and posterior boundaries of the base of support (the lines connecting left and right metatarsal five and the left and right heel) into the coordinate system of the force plate. By using this procedure, the position of the COP could be calculated in relation to the boundaries of the base of support for each subject and each condition. Specific care was taken that all subjects placed their feet in exactly the same position on the force plate for all measurements. Subjects were instructed not to reposition or move their feet out of this position during the tasks. The arms were held at the side of the body and no arm movement or counter rotation actions were allowed during the measurements. A trial was marked as “failed to cope with the task” in cases where the subjects increased their base of support by stepping or moving the feet and/or by performing counter rotation actions by using the arms or upper body.

All subjects performed six different tasks during upright standing on the force plate. These six tasks were performed in two series of experiments. In the first block of measurements, the limits of stability were examined during forward and backward leaning. Subjects were instructed to lean as far as possible forwards and then backwards without needing a lunge step or falling and without moving joints other than the ankle joints as an inverted pendulum. Each lean was closely observed by the investigators to ensure this was done correctly. Both tasks were repeated three times. The trials showing the least difference between the most anterior or the most posterior position of the COP under the feet and the anterior and posterior boundaries of the base of support were taken for each subject (A_{dist} and P_{dist}).

The experimental protocol in the second block consisted of 30 seconds of quiet standing under four conditions: eyes open (EO), eyes closed (EC), eyes open with vibration of the Achilles tendon (EOV) and eyes closed under vibration of the Achilles tendon (ECV). The vibration stimulus was applied by pneumatic driven purpose-built vibrators (1.5 mm amplitude, 80 Hz sinusoid) for the entire 30 seconds during standing. Before the measurements, subjects were seated on a chair in front of the force plate, both feet placed on the marked lines on the force plate. At this time, for the vibration conditions, the vibration devices were placed carefully on the left and right Achilles tendon approximately 3 cm above the insertion of the Achilles tendon to the calcaneus. Following that, the subjects stood up and the chair was removed. Subjects were instructed and encouraged to remain standing as long as possible during the 30 seconds recording trials. Each condition was repeated three times and the means of the three trials were used for further analysis. By using a custom-made LabVIEW routine (Labview 6.3 National Instruments, Austin Texas, USA) both systems (vibration and force data) were synchronized to start and stop at the same time. To be sure that the visual system was eliminated during the EC conditions, black out glasses (custom-made) were used. Photoreceptor stimulation via light reaching the retina through the eyelids alone was not expected to lead to differences in balance outcomes, at least in the healthy control subjects (Yelnik et al 2015). However, the blackout glasses ensured consistent lighting conditions for all participants, and excluded the possibility that light through the eyelids may affect the outcome measurements. Before the measurements, the vibration was applied for 5 seconds for each subject while sitting in order to allow the subjects to become accustomed to the vibration without muscle tension before onset of the measurements. All subjects were informed about the procedure of the measurements. No instructions were given to the subjects regarding gaze fixation during the EO conditions.

The force signals were passed through a digital Hamming low-pass filter with a cut-off frequency of 5 Hz for removing the high frequency noise and for eliminating the error of sampling. Based on the four-sensor ground reaction force data, the COP over time was calculated for both anteroposterior and mediolateral directions using a custom-made MATLAB routine (The Mathworks, Inc, Massachusetts, U.S.A., ver. R2010b). The postural stability was evaluated by means of the following parameters: the total excursion distance of the COP (COP_{Path}); the distances between the most anterior and posterior points of the COP_{Path} and the anterior and posterior boundaries of the base of support (COP_{Amin} and COP_{Pmin}); the corrected COP_{Amin} and COP_{Pmin} taking the limits of stability into account using the COP data from the leaning task (i.e. by subtracting the A_{dist} and P_{dist} from the COP_{Amin} and COP_{Pmin}). For a graphic representation of the calculation of these parameters, see Fig. 1. Application of vibration with eyes closed (ECV) lead to lunge steps in none of the healthy subjects but lead to lunge steps in five UPVD patients, who required extra steps and assistance of the safety harness and/or a staff member to maintain balance. These participants' data were excluded from the COP_{Path} analysis due to the time-dependent nature of the parameter, but the available COP data up until the initiation of their stepping were included in the COP_{Amin} and COP_{Pmin} analysis. Due to signal artefacts in the data, three control participants and two patients were excluded from the analysis.

Statistics

A two-way repeated measures analysis of variance (ANOVA), with subject group (UPVD patients and healthy controls) and task condition (EO, EC, EOV, ECV; dependent variable) as factors was used to determine differences in the analysed parameters (COP_{Path}, COP_{Amin}, COP_{Pmin}, corrected COP_{Amin}, corrected COP_{Pmin}) and hence, to examine the static balance maintenance of the participants under EO, EC EOV and ECV conditions. For each significant result, we applied simple contrasts to further investigate whether the outcome measures at certain task condition differed from EO or whether differences between subject groups or task condition existed. The A_{dist} and P_{dist} for the UPVD patients and healthy controls were checked for differences using an independent samples t-test. The level of significance for all tests was set at $\alpha = 0.05$. Before applying the statistical analyses, the distribution normality of our results for each variable was checked using the Kolmogorov–Smirnov Test, which revealed normal distributions (P values >0.05). Statistical analyses were carried out with STATISTICA 7.1 (StatSoft Inc., Tulsa, OK, USA). All results are presented as mean and standard deviation (mean and SD).

Results

Representative data for all task conditions, including the leaning task, of one patient with UPVD and one control participant can be seen in Fig. 1. The leaning task did not reveal differences between the control group (n = 14) compared to the patient group (n = 15) in either the anterior (P = 0.09) or posterior (P = 0.14) directions (Fig. 2). The two way repeated measures ANOVA with subject group (CONT: n = 14; UPVD: n = 10) and task condition as factors revealed a significant subject group effect ($F(1, 22) = 20.7$, $P < 0.001$), task condition effect (Greenhouse-Geisser corrected: $F(2.11, 46.36) = 259.99$, $P < 0.001$) and task condition x group interaction (Greenhouse-Geisser corrected: $F(2.11, 46.36) = 6.98$, $P < 0.01$) for the COP_{Path} (Fig. 3). Post-hoc Duncan's tests revealed significant differences between subject groups in the EOV ($P < 0.01$) and ECV ($P < 0.001$) tasks (Fig. 3). The minimum and maximum values for the COP_{Path} for the controls were 0.11m and 0.25m, 0.15m and 0.36m, 0.41m and 0.92m, 0.53m and 1.29m, and for the patients were 0.12m and 0.45m, 0.18m and 0.46m, 0.58m and 1.16m, 1.07m and 1.60m for the EO, EC, EOV and ECV task conditions respectively.

Insert Figures 1, 2 and 3.

Concerning the COP_{Pmin}, UPVD patients (n = 15) showed significantly lower values compared to the control group (n = 14) for all examined conditions (subject group effect: ($F(1, 27) = 5.89$, $P < 0.05$); task condition effect: (Greenhouse-Geisser corrected: $F(2.1, 56.58) = 108.56$, $P < 0.001$); no interaction; Fig. 4). The minimum and maximum values for the COP_{Pmin} for the controls were 0.09m and 0.15m, 0.09m and 0.15m, 0.03m and 0.12m, 0.03m and 0.12m, and for the patients were 0.06m and 0.12m, 0.05m and 0.13m, 0.03m and 0.09m, 0.03m and 0.10m for the EO, EC, EOV and ECV task conditions respectively. Similar differences were found when the corrected COP_{Pmin} was considered (subject group effect: ($F(1, 27) = 10.75$, $P < 0.01$); task condition effect: (Greenhouse-Geisser corrected: $F(2.1, 56.58) = 108.56$, $P < 0.001$); no interaction; Fig. 4). The minimum and maximum values for the corrected COP_{Pmin} for the controls were 0.04m and 0.11m, 0.04m and 0.11m, -0.04m and 0.07m, -0.03m and 0.08m and for the patients were 0.004m and 0.07m, 0.006m and 0.07m, -0.03m and 0.04m, -0.03m and 0.04m for the EO, EC, EOV and ECV task conditions respectively. In contrast to the posterior direction, there was no subject group effect or interaction found for the COP_{Amin} (range across all tasks for the patients: 0.04m to 0.17m; and controls: 0.003m to 0.18m) or the corrected COP_{Amin} (range across all tasks for the patients: -0.03m to 0.12m; and controls: -0.04m to 0.12m).

Insert Figure 4.

Discussion

The aim of this study was to examine the contribution of the visual and proprioceptive systems to standing postural control through the absence of visual sensory input using black out glasses and vibration of the Achilles tendon in UPVD patients and healthy control subjects. It was hypothesized that disturbance of visual and proprioceptive systems would increase the postural sway in patients with UPVD to a greater extent than in healthy subjects, thereby revealing a reduced balance maintenance ability in the patients. This hypothesis was supported, as the UPVD patients showed a greater COP_{Path} and a smaller COP_{Pmin} than the controls in all tasks. The subject group x task condition interaction found in the COP_{Path}, with significant subject group differences for the vibration tasks, suggests that the patients were more severely affected by the vibration task conditions compared with the controls. As well as this, five out of the 17 (29%) patients could not complete the ECV task, underlining the proprioceptive reliance in the UPVD patients.

During the leaning task without any disturbance of the visual or proprioceptive systems, the A_{dist} and P_{dist} of the UPVD patients differed only negligibly from the healthy subjects. However, smaller absolute values in the UPVD patients were observed (about 0.9 cm (relative difference: 16%) and 0.7 cm (14%) in the anterior and posterior directions respectively). While one could argue that anxiety related to falling during the leaning tasks may have had a small effect on the results, all participants were secured in a safety harness and were aware that they could not fall. The base of support during dynamic gait tasks using three dimensional motion capture techniques is often calculated using the anterior toe markers which are placed at the same position on all subjects (McCrum et al. 2014, Süptitz et al. 2012, Süptitz et al. 2013). Our findings suggest that previous studies using the base of support in UPVD patients and healthy controls during dynamic tasks and assumed an equivalent base of support relative to foot size between the groups may have overestimated the actual base of support of the patients. For example, McCrum et al. (2014) found smaller base of support and margin of stability values at various points during a trip recovery task in UPVD patients compared with controls, but if the smaller corrected base of support values found in this study would have been taken into account, the differences found between groups may have been even more pronounced. We therefore recommend that future research could consider the individual base of support of subjects when possible and not estimate the base of support based on anatomical landmarks.

The COP_{Pmin} and corrected COP_{Pmin} were lowest in both subject groups under the vibration conditions, with significantly lower values for the patients compared to the healthy group in all conditions. Moreover, five out of the 17 (29%) UPVD patients could not complete the ECV condition task without taking lunge steps or falling backwards, meaning that our results may underestimate the true deficit of the UPVD group. Together with the greater effect of the EOV condition compared to the EC condition on stance stability, we suggest that proprioception is more important during stance in UPVD patients than vision for controlling stability. It has been shown that Achilles tendon vibration in healthy standing subjects leads to an illusion of forward motion in the first few seconds after onset of the stimulus, followed by a real backward movement intended to correct for the perceived forward motion (Barbieri et al. 2013, Thompson et al. 2007). The current results are in accordance with this, with the additional finding that control of the compensating backward shift seems to have been more difficult for the UPVD patients, reflected in the COP_{Pmin} and corrected COP_{Pmin} results.

The COP_{Path} in all conditions was greater for the UPVD patients compared with the healthy controls, suggesting that even when the patients could use their visual and proprioceptive systems, their sensory compensation was not sufficient to perform such standing balance tasks to the same level as healthy subjects. These results agree with previous studies that have shown lower postural stability in vestibulopathy patients compared with healthy subjects during stance (Aoki et al. 2014, García et al. 2012, Yeh et al. 2014) and decreased postural stability when one or more sensory systems are disturbed (Pavlou et al. 2011, Peterka 2002, Spiliopoulou 2012). It also appears that during quiet standing, disturbance of the proprioceptive sensory system leads to less stable stance than when the visual system is disturbed in both healthy subjects and UPVD patients, with stability in the posterior direction being particularly affected in the UPVD patients. This is in agreement with a previous study that found an increased reliance on proprioception in unilateral vestibulopathy under proprioceptive disturbance (Peterka et al. 2011). The current results, in combination with previous studies, indicate that when one sensory system is dysfunctional, such as in the patients with UPVD, an increased reliance on the remaining systems occurs. As a result, a disturbance or perturbation to one of the remaining systems leads to an exaggerated response in comparison with healthy subjects. For tasks such as bipedal stance, one could suggest that proprioception is more important than visual information due to the static, and relatively low visually-demanding, nature of the task, which would account for current and previous findings of a higher reliance on proprioception for stance (Peterka et al. 2011).

It is important to note that while the patients all had unilateral vestibulopathy, the degree of compensation varied. The degree and frequency of the symptoms varied from patient to patient. In addition, while all patients had been diagnosed at least six months prior to the measurements and remained uncompensated, the time since initial diagnosis varied and was not known for all subjects. The exact degree of compensation was also not known for all patients. However, there were no prominent outliers in our results, suggesting that while the vestibular function may have varied between patients, the overall impact on balance during stance was reasonably consistent. As we treated these subjects as a group with generalised balance disorders that should be distinct from healthy subjects in the conducted measures, this was not a concern for our results or conclusions. Of the five patients who needed to take a step during the ECV task, three had experienced a fall in daily life in the last 6 months. However, two steppers did not experience a fall in the last 6 months, and the one remaining faller managed to cope with the task, so it is unclear if task performance was related to falls history. Another consideration is that, while our subjects did not report any sensation related to the vibration in the soles of the feet, we cannot completely exclude the possibility that the vibration may have travelled via the calcaneus to the mechanoreceptors in the soles of the feet. That being said, when we compare this possibility to the methods normally used to inhibit mechanoreceptor sensory input via ice or anaesthetic being applied to the soles of the feet, we do not expect any significant effects of vibration on the mechanoreceptors that would alter our results.

In conclusion, a greater reduction in stance stability is seen when the proprioceptive sensory system is disturbed, compared to when the visual system is disturbed in both healthy subjects and UPVD patients. UPVD patients, in particular, show more difficulty in controlling postural stability in the posterior direction with visual and proprioceptive sensory disturbance. The individual limits of stability should be considered in future research when conducting posturographic measurements in vestibulopathy and other groups, as differences between subject groups may lead to erroneous comparisons.

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Declaration of Interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the paper.

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Figure Legends

Figure 1: (A): Schematic diagram of a representative trial of a control subject demonstrating the definitions and calculations of the COP parameters used in this study. A/P_{bound}: Anterior and posterior physical boundary of the base of support (the lines connecting left and right metatarsal five and the left and right heel respectively) $A/P_{leanlimit}$: The most anterior and posterior points of the COP during forward and backward leaning respectively. For other definitions, please see the abbreviations list. **(B):** Representative data from one patient with UPVD and one control subject for the anterior and posterior leaning task and each quiet standing task condition.

Figure 2: The distance between the most anterior point of the centre of pressure (COP) during forward leaning and the anterior boundary (the line connecting left and right metatarsal five) of the base of support (Anterior) and the distance between the most posterior point of the COP during backward leaning and the posterior boundary (the line connecting the left and right heel) of the base of support (Posterior) for UPVD patients (n = 15) and healthy controls (n = 14).

Figure 3: The centre of pressure total path length (COP_{Path}) for UPVD patients (n = 10) and healthy controls (n = 14) during quiet standing under eyes open (EO), eyes closed (EC), eyes open with Achilles tendon vibration (EOV) and eyes closed with Achilles tendon vibration (ECV).

1: Significant difference to EO ($P < 0.01$).

2: Significant difference to EC ($P < 0.01$).

3: Significant difference to EOV ($P < 0.01$).

*: Significant difference between subject groups ($P < 0.01$).

Figure 4: The distance between the most posterior point of the COP_{Path} and the posterior boundary of the base of support (COP_{Pmin}) and the corrected COP_{Pmin} (COP_{Pmin} minus the P_{dist}) for UPVD patients (n = 15) and healthy controls (n = 14) during quiet standing under eyes open (EO), eyes closed (EC), eyes open with Achilles tendon vibration (EOV) and eyes closed with Achilles vibration (ECV).

*: Significant subject group effect (P < 0.05).

#: Significant task condition effect (P < 0.001).

Figures

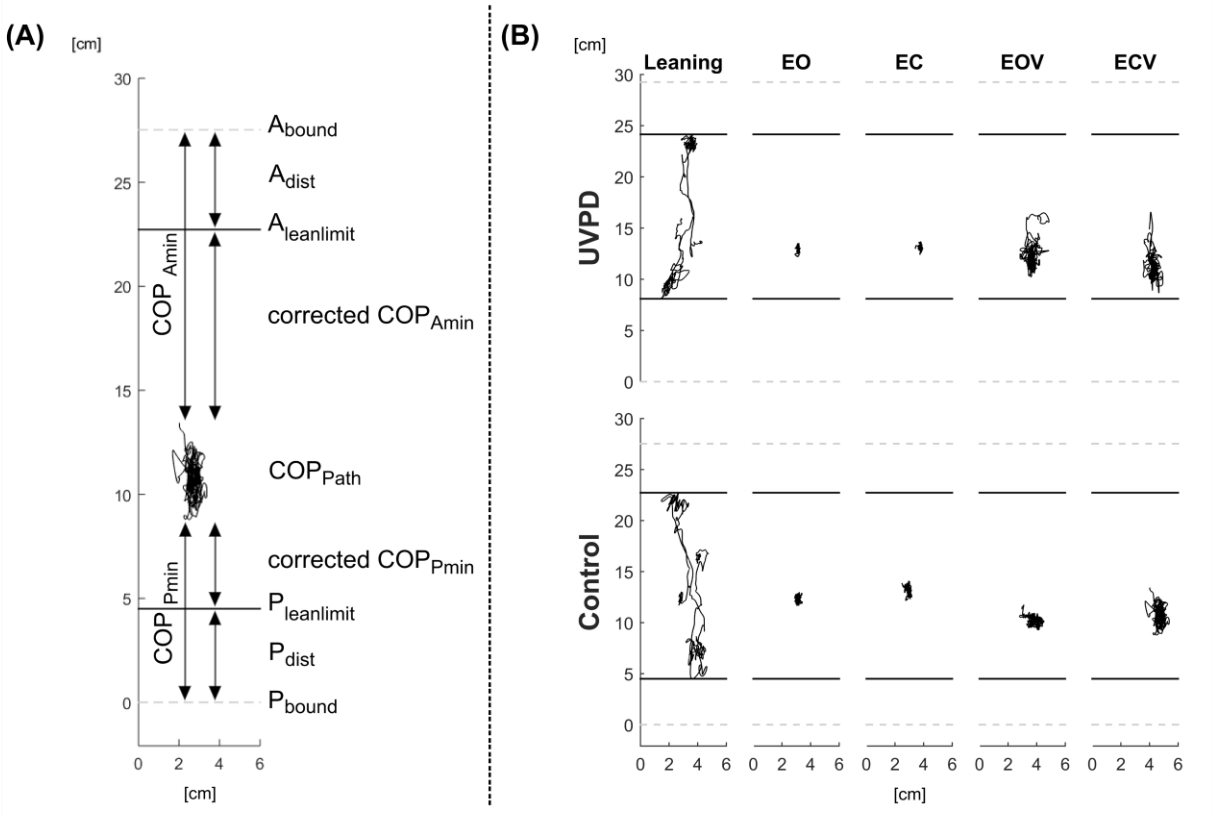


Figure 1

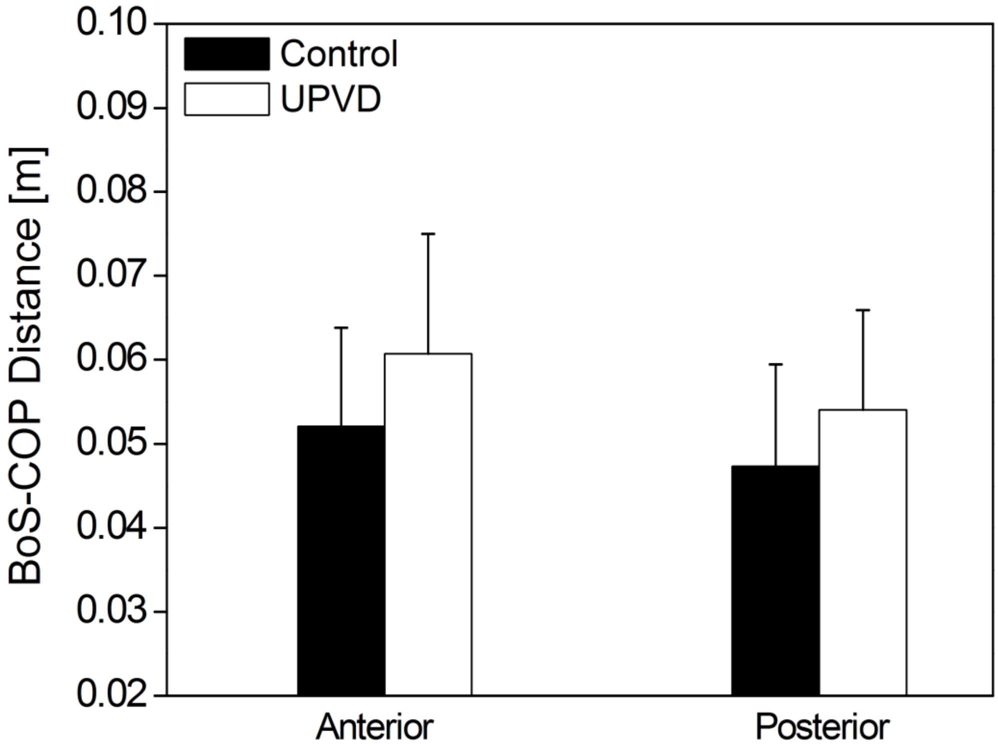
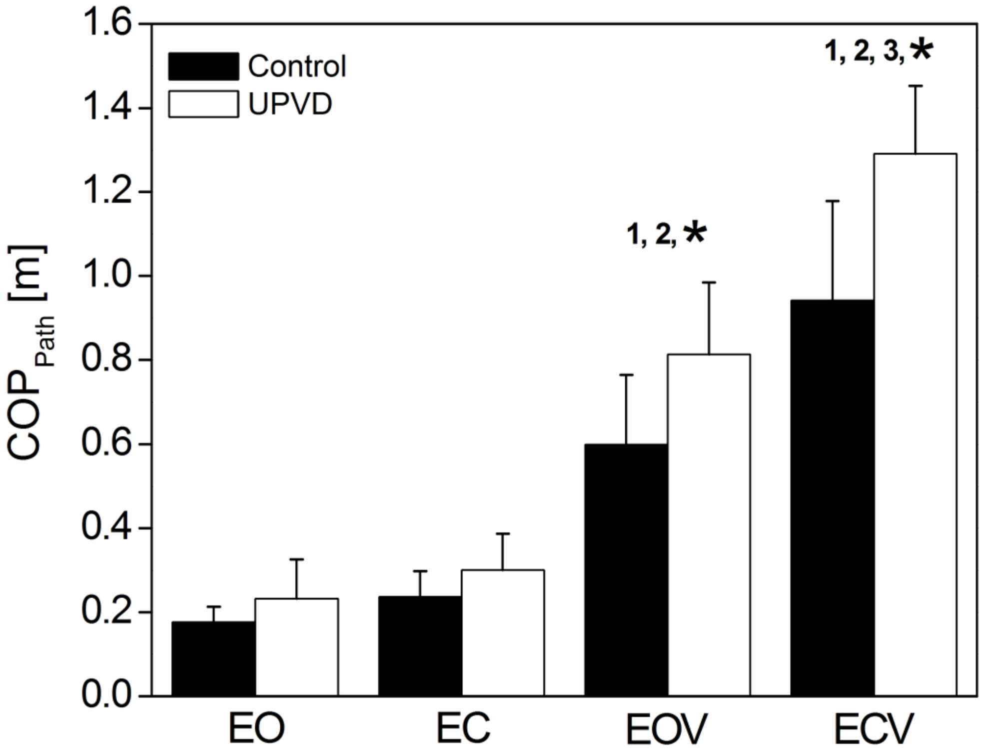

0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
Control
UPVD
BoS-COP Distance [m]
Anterior
Posterior

Figure 2



1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
COP$_{Path}$ [m]
Control
UPVD
1, 2, *
1, 2, 3, *
EO
EC
EOV
ECV

Figure 3

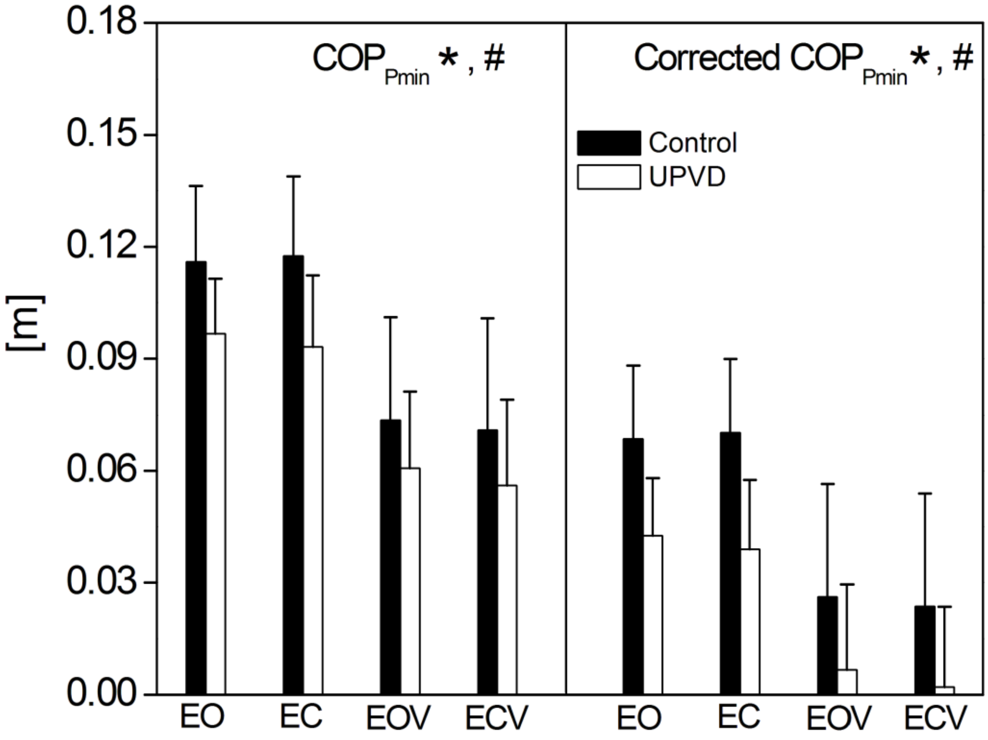

0.18
0.15
0.12
0.09
0.06
0.03
0.00
[m]
COP Pmin *, #
Corrected COP Pmin *, #
Control
UPVD
EO
EC
EOV
ECV
EO
EC
EOV
ECV

Figure 4