Day-to-day variation in sleep quality and static balance: results from an exploratory study.

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Abstract— **Sleep plays a critical role in promoting health and wellbeing. Variations in sleep quality and pattern may effect human balance. This study investigated whether day-to-day variations in sleep quality result in balance deteriorations during quiet standing. Ten healthy volunteers underwent sleep and balance assessment over two consecutive days. Sleep quality was assessed using sleep diaries, whereas balance was assessed in a gait laboratory to measure Center of Pressure (CoP) and Center of Mass (CoM) displacement. Results demonstrated an association among worsening in sleep quality and CoP displacement measures, both with eyes open and closed. The correlation coefficients between CoP and CoM also showed significant differences in subjects reporting a sleep worsening over the two days. These results suggest that short-term worsening in sleep quality may affect our balance and its associated mechanisms of control.**

Keywords— **sleep quality, balance, posturography, postural steadiness**

I. Introduction

Sleep plays a critical role for health and wellbeing [1]–[4]. Moreover, there is compelling evidence of the adverse effects that sleep deprivation can have on physical and mental health, as well as on daytime performance and personal safety [5]. Previous studies have investigated the effects of long intervals (i.e. 24 to 36 hours or more) of sleep deprivation on postural control during quiet standing [6]–[9]. In addition, a recently published study [10] investigated the effects of chronic low sleep quality on postural control.

Differently, the study described in this paper explored whether day-to-day variation in sleep quality may affect static balance, i.e. postural steadiness during quiet standing.

II. Materials and methods

A. Study participants

Ten healthy volunteers (mean±S.D.: age 27.6±2.6 years, height 174.5±11.2 cm, weight 75.3±11.2 kg) with no known sleep or balance problems were enrolled through an e-mail advert sent to postgraduate students of the School of Engineering of the University of Warwick. Prior to their participation, subjects signed a written informed consent. The study was approved by the Biomedical and Scientific Research Ethics Committee of the University of Warwick (reference number REGO-2014-1039).

B. Equipment

Kinetic and kinematic data were collected for each subject during a series of quiet standing trials carried out at the Gait Laboratory of the School of Engineering, University of Warwick. These data allowed computing the position of the center of pressure (CoP) and the center of mass (CoM).

Kinetic data was collected using a tri-dimensional force plate (Advanced Mechanical Technology, Inc., Watertown, MA, USA) at a sampling frequency of 1 kHz.
Kinematic data was collected using a 12 infrared-camera motion capture system (Vicon Motion Systems Ltd., Oxford, UK) at a sampling frequency of 200 Hz. Twenty-seven reflective body markers were affixed to participants according to the set-up instructions provided by the manufacturer for a full-body biomechanical model.

C. Protocol

Subjects underwent sleep and balance assessments for two consecutive nights and days, respectively.

Sleep assessment was based on the Consensus Sleep Diary (CSD). The CSD yields information about relevant sleep metrics (i.e. sleep latency, wakefulness after initial sleep onset, total sleep time, total time spent in bed, sleep efficiency and sleep quality) [11]. Face-to-face meetings were held with the participants during which they were familiarized with the structure and contents of the CSD. They were instructed to fill it out each morning immediately after getting out of bed during their participation in the study. The CSD provided us with a subjective global appraisal of each night's sleep quality.

Balance assessment was carried out in two sessions per participant. These sessions started at 9, 10 or 11 a.m., but the starting time was kept constant for each participant to minimize the effects of individual circadian phase. Each session, 27 reflective body markers were affixed to the participant's body using hypoallergenic, double-sided tape. The participants were barefoot and wore tight fitting clothes to reduce the movement of the markers. Subsequently, participants were asked to complete a series of eight quiet standing trials: four trials with eyes open (EO) staring at a fixed point on the wall in front of them, alternated with four trials with eyes closed (EC). The duration of each trial was 30 seconds. Participants were instructed to stand quietly near the center of the force plate with their feet side-by-side in a comfortable position and arms hanging relaxed at their sides. A short resting interval was allowed between trials.

D. Data processing

The default algorithms embedded in the software Vicon Nexus 1.4.116 (Vicon Motion Systems Ltd., Oxford, UK) were used to compute the CoP and CoM positions from the kinetic and kinematic data, respectively. The outputs of these computations were: 1) a time-series for the CoP position expressed by its anteroposterior (AP) and mediolaterial (ML) coordinates; and, 2) a time-series for the CoM position expressed by its AP, ML and vertical (VT) coordinates. Hence, these time-series contain the trajectory of both CoP and CoM for the duration of the trials. These time-series were processed as follows.

The anteroposterior (AP) and mediolateral (ML) components of the CoP time-series were passed through a fourth-order zero-phase Butterworth low-pass digital filter with a cutoff frequency of 3 Hz as in [12]. Subsequently, the initial and last five seconds of each trial were discarded to account for the "adaptation phase" of the participant to the quiet standing task and to avoid the effects of fatigue or lack of attention associated to a sustained task, respectively, as suggested in [13]. The remaining 20 s (20,000 samples) were detrended (i.e. the mean was subtracted), given that the analysis of the CoP displacement was carried out relative to its mean position and not to the origin of the coordinate system located at a corner of the force plate. Finally, six time-domain CoP displacement measures drawn from three families (i.e. distance, velocity and area) were computed from the processed data as described by Duarte *et al.* [14]. Table 1 shows the descriptions of these measures. Total length, Total velocity and Area-CE were computed by using together the AP and ML components of the CoP time-series. In contrast, Standard deviation, Amplitude and Mean velocity were computed for each component separately.

Table 1. Description of center of pressure displacement measures

Family / Measure (units)	Description
Distance (mm) /	
Total length	Length of the CoP trajectory
Standard deviation	Dispersion of the CoP position around its mean position computed separately for AP/ML directions
Amplitude	Distance between the minimum and maximum positions computed separately for AP/ML directions
Velocity (mm/s) /	
Mean velocity	Total displacement in each direction (AP/ML) divided by the length of the time-series in seconds
Total velocity	Total length divided by the length of the time-series in seconds
Area (mm^2) /	
Area-CE	Area of the ellipse that contains 95% of the CoP points

CoP: center of pressure; AP: anteroposterior; ML: mediolateral

Similarly, the AP and ML components of the CoM signals were passed through a fourth-order zero-phase Butterworth low-pass digital filter with a cutoff frequency of 1.5 Hz as in [12]. Moreover, the central 20 s (4,000 samples) were extracted and detrended for further analysis. Finally, Pearson correlation coefficients (*r*) between CoP and CoM time-series in the AP and ML directions were computed for each trial (hereafter referred to as CoP-CoM correlations). Downsampled versions (factor=5) of the CoP time-series were used during this step to match the length of both time-series.

Scripts for data processing were written using Matlab v2016b (The Mathworks, Inc., Natick, MA, USA).

E. Statistical analysis

Using the information reported in the sleep diary (namely, self-rated sleep quality) participants meeting one of the following conditions were identified: 1) those reporting no variation in sleep quality over two consecutive days (group 1); and, 2) those reporting a "(very) good" sleep quality on one day and a "(very) poor" sleep quality on the other (group 2). Accordingly, the datasets containing CoP displacement measures and CoP-CoM correlations were divided in subset 1 and subset 2 for further statistical analysis.

Wilcoxon signed rank tests using sleep quality as grouping factor were performed on each CoP displacement measure and correlation coefficient for both groups. A non-parametric paired test was chosen given that: 1) most CoP displacement measures proved to exhibit non-normal distributions using the Shapiro-Wilk normality test; and, 2) paired observations for each participant were under investigation (e.g. "good" sleep versus "poor" sleep). Moreover, the p-values obtained from the statistical tests on each CoP displacement measure (non-applicable for CoP-CoM correlations) were adjusted using Bonferroni correction to compensate the possible increase in Type I errors generated by multiple comparison [15]. Specifically, adjusted p-values were calculated by multiplying the original p-values by 3, given that the computed CoP displacement measures were drawn from three families (i.e. distance, velocity and area). A p value < 0.05 was accepted as evidence of statistical significance.

Scripts for statistical analysis were also written using Matlab v2016b (The Mathworks, Inc., Natick, MA, USA).

III. Results

Three participants reported no variation in sleep quality over two consecutive days (group 1), whereas six participants reported "good" sleep quality for one day and "poor" sleep quality for the other (group 2). One patient reported variation from good to very good, therefore was not included in the any of the groups.

A. CoP displacement measures

None of the CoP displacement measures showed statistically significant differences for participants in group 1, neither for eyes open nor for eyes closed. In contrast, 2 and 6 CoP displacement measures exhibited statistically significant differences for participants in group 2 for eyes open and closed, respectively. Namely, Standard deviation and Amplitude, both in the ML direction, for eyes open; and, Total length, Total velocity and Mean velocity in both AP and ML directions, for eyes closed. Median differences (MD), mean absolute deviations (MAD) and p-values for each CoP displacement measure are provided in Table 2 for both groups and conditions (eyes open and closed). Non-parametric descriptive statistics (i.e. MD and MAD) were computed given the non-normal distribution of the data.

B. CoP – CoM correlation coefficients

Correlation coefficients between CoP and CoM in the AP and ML components did not show statistically significant differences in group 1, neither for eyes open nor for eyes closed. In contrast, correlation coefficients exhibited statistically significant differences in group 2 in the ML component for eyes open and in the AP component for eyes closed. P-values for correlations coefficients are provided in Table 3 for both groups and conditions (eyes open and closed).

IV. Discussion

Our results regarding differences in CoP displacement measures revealed that participants in group 2 showed larger CoP displacement variations (i.e. Standard deviation) and Amplitude in the ML direction after a "poor" sleep than after a "good" sleep when tested with eyes open. Additionally, those participants exhibited larger total CoP displacements and velocities (i.e. Total velocity and Mean velocity in the AP and ML directions) after a "poor" than after a "good" sleep when tested with eyes closed. These results suggest lower postural steadiness after a "poor" sleep.

Regarding correlation coefficients between CoP and CoM, our results suggest that day-to-day variation in sleep quality may indeed affect the underlying balance control system that aims to maintain our CoM inside our base of support (by means of CoP displacements).

V. Conclusions

To the best of our knowledge, this is the first study investigating the impact of day-to-day variations in sleep quality on balance during quiet standing. In this study, we have tested balance in a sample of healthy subjects that reported a "good" sleep for one night and a "poor" sleep for the next (or vice versa). We have found statistically significant differences for some CoP displacement measures, as well as for

Table 2. Summary of results for statistical testing of differences in center of pressure displacement measures between two consecutive days

	Group 1 (N=3)						Group 2 (N=6)					
	Eyes open			Eyes closed			Eyes open			Eyes closed		
Measure	MD	MAD	p	MD	MAD	p	MD	MAD	p	MD	MAD	p
Total length	14.55	14.88	0.08	28.39	36.27	0.19	6.57	14.23	0.63	12.81	8.73	**0.01**
Standard deviation, AP	0.48	1.14	0.45	0.49	1.11	0.70	0.01	0.52	2.66	0.20	0.37	0.44
Standard deviation, ML	0.37	0.91	0.61	0.42	0.57	0.13	0.29	0.37	**0.02**	0.08	0.28	1.53
Amplitude, AP	1.90	5.15	0.39	5.28	6.42	0.33	0.33	2.82	2.73	0.91	2.10	0.99
Amplitude, ML	2.84	3.50	0.33	2.15	3.76	0.28	1.26	2.41	**0.05**	0.24	1.47	1.94
Total velocity	0.73	0.74	0.08	1.42	1.81	0.19	0.33	0.71	0.63	0.64	0.44	**0.01**
Mean velocity, AP	0.43	0.50	0.13	0.94	1.31	0.23	0.24	0.48	0.37	0.64	0.34	**0.04**
Mean velocity, ML	0.43	0.51	0.10	0.43	0.91	1.02	0.08	0.51	1.22	0.26	0.24	**0.04**
Area-CE	64.92	119.51	0.45	70.77	65.05	0.39	14.00	37.42	0.37	15.49	30.02	0.51

AP: anteroposterior; ML: mediolateral

MD: Median difference; MAD: Median absolute deviation

Table 3. P-values for statistical testing of differences in CoP-CoM correlation coefficients over two consecutive days

	Group 1 (N=3)		Group 2 (N=6)	
Direction	EO	EC	EO	EC
Anteroposterior	0.46	0.27	0.30	**<0.01**
Mediolateral	0.84	0.23	**<0.01**	0.16

CoP/CoM: center of pressure/mass
EO: eyes open; EC: eyes closed

CoP-CoM correlations between "good" and "poor" sleep. These results suggest that the variation in sleep quality we experience from one day to the next may indeed affect our ability to maintain postural steadiness during quiet standing.

Nevertheless, further confirmation is needed through studies that incorporate elements that allow overcoming our study's limitations, namely, a larger sample size, an objective sleep quality assessment method (e.g. actigraphy), and a more complex model of balance and posture control (e.g. the inverted pendulum or multi-segment models) [16].

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Conflict of Interest

The authors declare that they have no conflict of interest.

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