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Applying entropy to human center of foot pressure data to assess attention investment in balance control

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***Abstract*—Assessing the amount of attention invested in the control of balance is crucial when evaluating balance abilities. The purpose of the present study was to examine the relevance of applying entropy to human center of foot pressure data to assess attention investment in balance control. To achieve this goal, young healthy adults were tested in a static postural task consisting in standing as immobile as possible with their eyes closed under $normal$, $altered$ (foam) and $improved$ (ankle-foot orthosis). The center of foot pressure displacements were recorded using a force platform. Three dependent variables were computed. Results showed decreased values of velocity and displacement of Center of Pressure (CoP), indicating a less important amount of postural sway, and increased values of Sample Entropy of CoP, suggesting a less amount of attention invested in the control of bipedal posture than when the somatosensation from the foot and the ankle was normal.**

***Index Terms*—Balance control, Attention investment, Sample entropy, Center of pressure**

I. INTRODUCTION

POSTURAL control is a tangle of interactions between multiple sensory systems: the vestibular, the somatosensory and the proprioceptive ones. All these information are integrated by the central nervous system sensors and result in an automatic regulation of the balance through different feedback loops. For young healthy individuals, maintaining quiet stance is an easy task which calls up minimal attention resources. However, in more challenging conditions such as the simultaneity of a more cognitively demanding task and/or the absence of some sensory input, postural control requires a greater attention investment to avoid falling. The former case, known as dual-task paradigm, is very common in daily living (e.g. talking while standing or walking) and was intensively investigated. In the second case, a healthy individual is expected to adapt himself and compensate unconsciously by re-weighting the different afferent information while an elderly or impaired individual is expected to need to call up additional attention resources at the expense of automaticity.

Sensory-motor and cognitive mechanisms involved in the control of balance have been studied, until recently, through the computation of conventional measures based on summary statistics of the center of foot pressure (CoP) displacements. These measures provide an overall view of the postural sway and of the muscular strategy adopted (hip- or ankle-strategy) but they do not give insights neither into the control strategy, nor the attentional demand allocated to the control of balance. Deepening the understanding of the mode of control and of its underlying mechanisms has encouraged researchers to call for more powerful and relevant techniques of analysis. Nonlinear methods turn out to be successful tools for the analysis of the dynamical structure of the CoP displacements during quiet standing (RQA [1], [2], DFA, Lyapunov Exponent [3], etc.). Among these parameters, entropy is of interest for quantifying the regularity of the considered time series. One of the most appropriate method to compute entropy of such signals is Sample Entropy that was applied to various physiological time series (HRV [4], gait [5], and noteworthy to CoP displacements during the control of upright posture [3], [6]–[8]). Very interestingly, results of numerous recent studies, which assessed postural control when manipulating the cognitive load during the execution of the postural task (through the concurrent performance of a cognitively demanding task, for instance), suggest that SEn_{CoP} could reflect attention investment: the less attention-demanding the task, the greater entropy. That way, healthy individuals and experts are expected to exhibit greater entropy synonymous with automaticity and adaptability. Smaller values of entropy, reflecting regularity, are in turn associated with movements confined to repetitive patterns without possibility to adapt oneself to new challenges or situations as observed among the elderly or disabled people. However, the interpretation of SEn_{CoP} is not always straightforward [6] and may be gained from completing the analysis with more traditional measures quantifying the postural sway.

The purpose of the present study is to examine the relevance of applying entropy to human center of foot pressure data to assess attention investment in balance control. We hypothesized that (1) altering somatosensory inputs from

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the foot and the ankle would increase CoP fluctuation and decrease CoP entropy, whereas (2) facilitating somatosensory inputs from the foot and the ankle would decrease CoP fluctuation and increase sample entropy of the CoP. To our knowledge, although the effects of foam support on the control of bipedal posture has already been assessed in terms of CoP regularity/predictability using sample entropy of the CoP parameters (e.g. in [6]) no study has evaluated, in the same experimental procedure, whether and how experimentally *degrading*, but also *improving* somatosensory inputs from the foot and ankle modifies attention investment in balance control, as assessed by sample entropy of the CoP.

After this introduction and state-of-the-art, the paper is divided as follows. In section II, the two experimental protocols are described and the method used for data analysis is detailed. Finally, results are presented in section III and discussed in section IV.

II. MATERIAL AND METHODS

A. Subjects

Ten young male, university students, participated in Experiment 1. Ten other young male, university students, took part in Experiment 2. They gave their informed consent to the experimental procedure as required by the Helsinki declaration (1964), and were naive as to the purpose of the experiment. Subjects included in the study had to demonstrate neither history of motor problem, neurological disease nor vestibular impairment.

B. Experimental procedure

With eyes closed, subjects stood barefoot on the force platform in a standardized position (feet abducted at 30°, heels separation 3 cm), arms hanging loosely by their sides and were asked to stand as still as possible.

In experiment 1, the postural task was executed in two support surfaces conditions (Firm and Foam). The force platform served as the Firm support surface. In the Foam condition, a 2-cm thick foam support surface, altering the quality and/or quantity of somatosensory information at the plantar sole and the ankle, was placed under the subjects' feet.

In experiment 2, the postural task was executed in two No-AFO and AFO condition. In the AFO condition, subjects were asked to wear an AFO (Thuasne, Levallois-Perret, France) on each foot.

The order of presentation of the two Firm and Foam support conditions (Experiment 1) and the two conditions of No-AFO and AFO (Experiment 2) was randomized over subjects. For each condition, subjects performed three 32s trials.

C. Measurements and data analysis

A force platform (Equi+, model PF01, Aix les Bains, France), consisted of an aluminum plate (80 cm each side) laying on three uni-axial load cells (0-50 daN), was used to measure the displacements of the CoP. Signals from the force platform were sampled at 64 Hz. Given that the effect of filtering on non-linear analysis is still debated, data were not filtered in this study [9]. The antero-posterior and medio-lateral CoP time series were centered on zero mean prior to constructing the resultant distance (RD) CoP time series. Specifically, RD is the vector distance from the center of the posturogram to each pair of points in the antero-posterior and medio-lateral time series.

On the one hand, to assess the postural performance, we quantified the amount and the control of postural sway by calculating:

1) The root mean square of the CoP displacements $A_{CoP} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} RD_i^2}$ (in mm)
2) The root mean square of the CoP velocities $V_{CoP} = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N-1}(\frac{RD_{i+1}-RD_i}{\delta t})^2}$ (in mm/s)

where $\delta t = 0.016s$ and N is the number of samples.

On the other hand, to give insights into the dynamical structure and particularly into the regularity/predictability of the CoP trajectories, we calculated the sample entropy of the RD time series as follows [9], [10]:

1) The time series was normalized (zero mean and unit variance) to make the measure size- and scale-independent.
2) $m-$ and $(m+1)-$ dimensional embedding vectors were constructed with a time delay equal to 1 i.e. with consecutive points: $z_k = (RD_k, RD_{k+1}, ..., RD_{k+m-1})$ for $1 \leq k \leq N-m$ and $w_k = (RD_k, RD_{k+1}, ..., RD_{k+m-1}, RD_{k+m})$ for $1 \leq k \leq N-m-1$.
3) For $1 \leq i \leq N-m$, the probability $B_r^m(i)$ that another $m-$dimensional embedding vector is close to z_i with a tolerance of $r\%$ of the standard deviation (SD) of the time series is calculated along with their mean $B_r^m = \frac{1}{N-m}\sum_{i=1}^{N-m} B_r^m(i)$: $B_r^m(i) = \frac{1}{N-m+1}\sum_{j=1,\ j\neq i}^{N-m} \Omega(r.SD - \max_{0\leq k\leq m-1}|RD_{j+k} - RD_{i+k}|)$ where Ω is the Heaviside function. In other words, B_r^m is the probability that two different sequences match for m points. In the same way, $A_r^m(i)$ are calculated for the $(m+1)-$dimensional embedding vectors w_i. and A_r^m is the probability that two different sequences match for $(m+1)$ points.
4) Finally, for N large enough $SEn_{CoP}(m, r, N) = -\log(CP)$ where $CP = A_r^m / B_r^m$. It is the negative natural logarithm of the conditional probability that a sequence of data points with length N, having repeated itself within a tolerance r for m points, will also repeat itself for $(m+1)$ points, without allowing self-matches [10]. Parameters values of m ($m = 3$) and r ($r = 0.05$) were based on the optimization procedure described by Ramdani [9]. Indeed, SEn_{CoP} was calculated for many couples (m, r), with m ranging from 1 to 6 and r from 0.05 to 0.5. A subset of m was extracted by observing a pseudo-convergence criterion of evolution of the median sample entropy depending on r for a given m. Then, the r minimizing, the maximum relative error of the

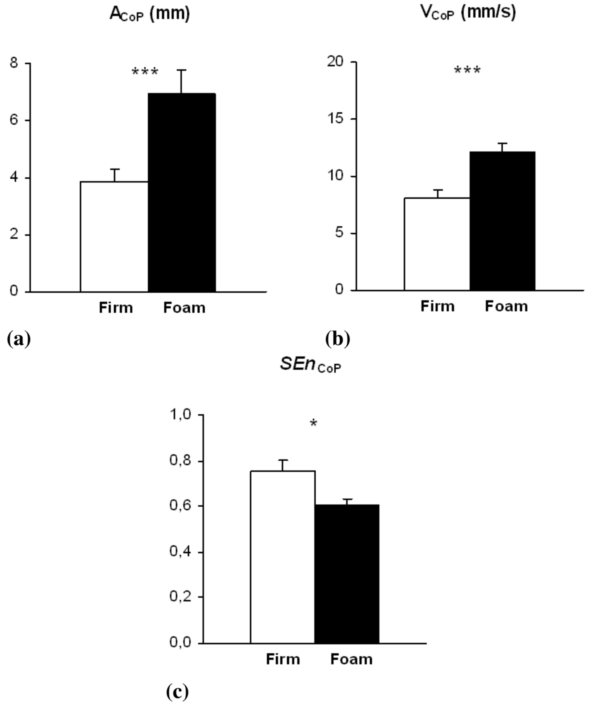

Fig. 1 Mean and standard error of mean of the variability (A_{CoP}) (panel A), the velocity (V_{CoP}) (panel B), and the regularity (SEn_{CoP}) (panel C) of center of foot pressure (CoP) trajectories obtained in the two conditions Firm and Foam conditions. These two experimental conditions are presented with different symbols: Firm (white bars) and Foam (black bars). The significant p-values for comparisons between Firm and Foam conditions also are reported (*: $p < 0.05$; ***: $p < 0.001$).

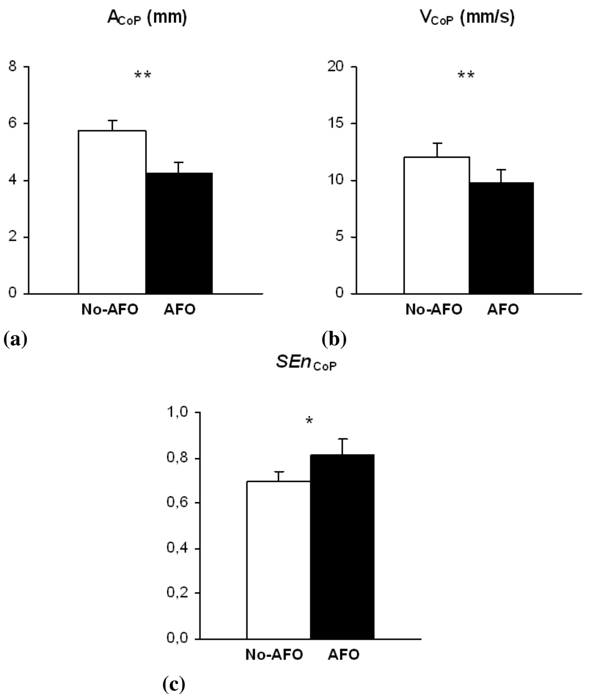

Fig. 2 Mean and standard error of mean of the variability (A_{CoP}) (panel a), the velocity (V_{CoP}) (panel b), and the regularity (SEn_{CoP}) (panel c) of center of foot pressure (CoP) trajectories obtained in the two conditions No-AFO and AFO conditions. These two experimental conditions are presented with different symbols: No-AFO (white bars) and AFO (black bars). The significant p-values for comparisons between No-AFO and AFO conditions also are reported (*: $p < 0.05$; **: $p < 0.01$).

entropy estimation and of the CP estimate, $Q(m,r)$ was chosen. This last quantity is defined by: $Q(m,r) = \max(\frac{\sigma_{CP}(m,r)}{CP(m,r)}, \frac{\sigma_{CP}(m,r)}{-\log(CP(m,r))CP(m,r)})$ where σ_{CP} is an estimate of the variability in the conditional probability CP.

D. Statistical analysis

The means of the three trials performed in the two experimental conditions were used for statistical analyses. A Kolmogorov-Smirnov test of equality of variances first showed that the distributions used for the analysis did not depart from normality ($p_s > 0.05$). For experiment 1 (respectively, experiment 2), data obtained for the Firm and Foam conditions (respectively, No-AFO and AFO conditions) were compared using two-tailed t-tests. Level of significance was set at 0.05.

III. RESULTS

A. Experiment 1

Analysis of the A_{CoP} showed smaller values in the Firm than Foam condition ($t = -5.07$, $p < 0.001$, Fig.1a). Analysis of the V_{CoP} showed smaller values in the Firm than Foam condition ($t = -6.54$, $p < 0.001$, Fig.1b). Analysis of the SEn_{CoP} showed larger values in the Firm than Foam condition ($t = 3.18$, $p < 0.05$, Fig.1c).

B. Experiment 2

Analysis of the A_{CoP} showed larger values in the no-AFO than AFO condition ($t = 4.70$, $p < 0.01$, Fig.2a). Analysis of the V_{CoP} showed larger values in the no-AFO than AFO condition ($t = 3.79$, $p < 0.01$, Fig.2b). Analysis of the SEn_{CoP} showed smaller values in no-AFO than AFO condition ($t = -3.13$, $p < 0.05$, Fig.2c).

IV. DISCUSSION AND CONCLUSION

Maintaining quiet standing is as well-experienced and rather automatic task as it may become very difficult from the moment that we are deprived of the complete use of our senses or that the environmental constraints are unusual or unexpected. Such circumstances of degraded postural control are notably observed within the elderly and are the primary cause of fall and related injuries. Looking for relevant and easy-to-use conditions of postural control assessment to give insight into attention investment in balance control is of great importance.

To assess the relevance of applying entropy to center of foot pressure to infer attention investment, young healthy adults were tested in a static postural task with their eyes closed. We remove visual information as it was previously shown to substantially reduce the postural effect caused by the manipulation of somatosensory information from the foot

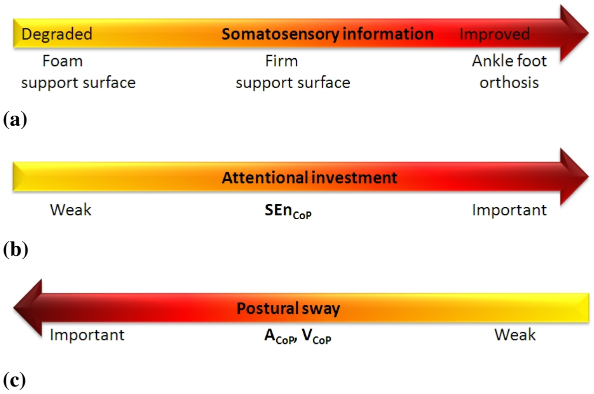

Fig. 3 Schematic overview drawing a parallel between the modulation of the somatosensory information (Panel a), the CoP regularity, automaticity of control and attention investment assessed with SEn_{CoP} (Panel b) and the postural sway assessed with A_{CoP} and V_{CoP} (Panel c). Improving the somatosensory context led to more irregular/unpredictable CoP trajectories, suggesting with less attention investment and greater automaticity. These results came with a decrease of the amount of postural sway highlighted by weak values of A_{CoP} and V_{CoP}.

and the ankle. When it was $degraded$ by standing on a foam surface, results showed increased values of both A_{CoP} and V_{CoP}, indicating a more important amount of postural sway, and (2) decreased values of SEn_{CoP}, suggesting a more important amount of attention invested in the control of posture. Conversely, when it was $improved$ by the orthosis, results showed decreased values of A_{CoP} and V_{CoP}, indicating a less important amount of postural sway, and (2) increased values of SEn_{CoP}, suggesting a less amount of attention invested in the control of bipedal posture than when the somatosensation from the foot and the ankle was normal.

Concerning the assessment of postural control for attention investment, [1], [2] assessed the control of posture during quiet standing in foam condition with RQA analysis of the CoP and found opposite results of entropy from ours. However, their measure of entropy is different from our and the closest parameter is the percentage of recurrence which increased in the foam condition for Schmidt indicating a more regular time series but decreased in the foam condition for Riley.

SEn_{CoP} was used to investigate the effect of support surface on the control of upright posture and was found to decrease in the foam condition in Stins et al. [7] and Strang et al. [11], but no significant effect was observed by Borg and Laxaback [6]. Discrepancies may be due to the features of foam support used: thickness and density of the foam. In our case, SEn_{CoP} decreased in the Foam condition in line with Stins et al. [7] and Strang et al. [11] and increased in the AFO condition in comparison with the control one. This means that the dynamical structure of the CoP displacements is more irregular with the AFO and more regular on the foam. In other words, the trajectories of the CoP are richer and unpredictable in the enhanced somatosensory condition from the foot and the ankle, whereas same patterns tend to repeat themselves in the degraded somatosensory condition from the foot and the ankle. In terms of control, this means that the AFO condition is less attention-demanding and is more automatic than the Foam condition is (Fig.3). These results about the attentional investment and automaticity are in line other results [6], [12]. The interpretation of entropy is not always straightforward because it depends on the attention invested, automaticity and noise. However, this difficulty may be overcame by combining SEn_{CoP} parameter with conventional measures. In this way, greater values of entropy associated with smaller postural sway may be interpreted as a complex fine tuned control of upright posture (Fig.3). Finally, a shift in mode of postural control occurred with somatosensory modulation and SEn_{CoP} turned out to be a relevant tool to detect and quantify its extent.

To conclude, taken together, results from experiment 1 and from experiment 2 lend supports the use of sample entropy as a suitable straightforward tool to assess the degree of automaticity in control of balance. These results are all the more encouraging that such monitoring and simple assessment of postural control may be easy to reproduce in a smart home environment by its integration into different acquisition systems embedded in several objects of daily living.

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