Selection of entropy-measure parameters for force plate-based human balance evaluation

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Abstract. Human balance is commonly evaluated through the center of pressure (COP) displacement measured with a force plate, producing 2D time-series that represent COP trajectories in the anteroposterior and mediolateral directions. Entropy measures have been previously used to quantify the regularity of those time-series in different groups and/or experimental conditions. However, these measures are computed using multiple input parameters, the selection of which has been scarcely investigated within this context.

This study aimed to investigate the behavior of COP time-series entropy measures using different parameters values, in order to inform their selection. Specifically, we investigated Approximate Entropy (ApEn) and Sample Entropy (SampEn), which are very sensitive to their input parameters: *m* (embedding dimension), *r* (tolerance) and N (length of data). A dataset containing COP time-series for 159 subjects with no physical disabilities was used. As a case study, subjects were grouped in young adults (age<60, n=85), and older adults (age≥60) with (n=18) and without (n=56) history of falls. ApEn and SampEn were computed for $m = \{2, 3\}$ and $r = \{0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5\}$ with a fixed data length (N=1200 points). ApEn and SampEn values were compared between groups using one-way ANOVA.

Our results suggest that ApEn and SampEn are able to discriminate with ease between young and older adults for a wide range of *m* and *r* values. However, the selection becomes critical for the discrimination between non-fallers and fallers. An $m = 2$ and $r = \{0.4, 0.45\}$ are suggested in this case.

Keywords: Entropy, Balance, Posturography

1 Introduction

Human balance is the result of a complex process which relies on the adequate integration of several physiological systems (i.e. visual, vestibular, somatosensory and musculoskeletal) [1]. Age-related disabilities and certain illnesses may affect one or more of those systems, potentially producing impaired balance and increasing the risk of falling [2]. Therefore, the characterization of human balance is of paramount importance for researchers and clinicians alike.

The most common measurement technique of body balance is static posturography (a.k.a. stabilography), i.e. the measure of the center of pressure (COP) displacement during quiet standing. The COP is the point location of the vertical ground reaction force vector. It is typically acquired with a force plate which outputs 2D time-series representing its trajectory in the anterior-posterior (AP) and medial-lateral (ML) directions. Subsequently, various measures are computed to characterize COP excursions and to investigate differences between groups and/or testing conditions. Linear and frequency measures have been extensively used for this purpose (e.g. total length, range in the AP/ML direction, mean and median frequencies of the time-series) [3–5].

More recently, nonlinear measures such as Approximate Entropy (ApEn) and Sample Entropy (SampEn) have been used to quantify the regularity or predictability within COP time-series in different groups or testing conditions [6–13]. Broadly speaking, ApEn and SampEn measure the likelihood that subseries of length m (from a time-series of length N) that are similar within a tolerance range given by $\pm r$ times the standard deviation of the time-series, remain similar for subseries of length m+1. A regular/predictable time-series (e.g. a signal containing patterns) produce relatively small entropy values, whereas a less predictable process (e.g. random noise) produce higher entropy values [14, 15]. The appropriate selection of parameters m (embedding dimension), r (similarity criterion) and N (data length) is critical; yet it has been scarcely investigated in COP time-series analysis.

This study aimed (1) to determine the adequate choice of input parameters m and r on the computation of ApEn and SampEn on the analysis of COP time-series; and (2) to determine the ability of ApEn and SampEn to discriminate between groups of young adults, and older adults with and without history of falls.

2 Methods

2.1 Data set description

A public data set of human balance evaluations was used in this study [16]. This dataset contains posturography data for 163 subjects, recorded while the subjects were standing still for 60 seconds in four different conditions: with eyes open on a firm surface, with eyes open on a foam mat, with eyes closed on a firm surface, and with eyes closed on a foam mat. Three trials per condition were recorded, producing 1930 trials in total (26 trials from 5 subjects were excluded). During these trials, 3D force (Fx, Fy, Fz) and moment (Mx, My, Mz) data were recorded at a sampling frequency of 100 Hz using a force plate. Subsequently, these data were smoothed using a 4th order zero lag Butterworth low-pass filter with a cut-off frequency of 10 Hz and were used to compute the center of pressure in the anterior-posterior and medial-lateral directions (COPx and COPy, respectively). Additionally, the dataset contains subjects' basic demographic, anthropometric, and health status data (e.g. age, height, weight, morbidities and disabilities), as well as other qualitative evaluations related to balance, fear of falling, physical activity and cognitive function. A detailed description of the protocol and resulting data set can be found in [16].

2.2 Data processing

Firstly, COP time-series were downsampled with a factor of 5 to achieve an effective frequency of 20 Hz, which resulted in time-series with a length of N=1200 data points (20 Hz x 60 s). This operation was performed in order to introduce a time lag of 5 for the computation of ApEn and SampEn (i.e. including every 5th point of the original time-series in their computation). This procedure has been applied in previous studies in order to reduce redundancy while preserving essential information [6, 7, 11, 13].

Subsequently, Approximate Entropy (ApEn) and Sample Entropy (SampEn) were computed for each COP time-series using all possible combinations of m={2, 3} and r={0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5}. A detailed description of the algorithms used to compute ApEn and SampEn can be found in [14] and [15].

2.3 Data analysis

Firstly, subjects were classified in three groups based on their age and history of falls in the past 12 months (falls12m): young adults (Y: age<60), older adults non-fallers (NF: age≥60 and falls12m=0) and older adults fallers (F: age≥60 and falls12m≥1). Subjects with physical disabilities were excluded from all groups, thus were not considered in the analysis. Subsequently, a one-way analysis of variance (ANOVA) was performed on basic demographic and anthropometric variables (i.e. age, height, weight and body mass index) to discard potential confounders, particularly in the investigation of differences in entropy values between the NF and F groups.

Finally, mean and standard deviation for each group were estimated for the ApEn and SampEn measures previously computed. The statistical significance of the differences in mean ApEn and SampEn values between groups was investigated by means of a one-way ANOVA. A p-value < 0.05 was taken as evidence of statistically significant differences between groups. Due to space constraints, only the results for anterior-posterior COP component are shown in this paper.

The scripts for data processing and analysis were written in MATLAB R2016b.

3 Results

Four subjects were discarded from the study due to physical disabilities (namely, poliomyelitis and cerebral palsy), leaving 159 subjects (115 females, 44 males) for the analysis: 85 subjects were classified as young adults (Y), 56 as older adults non-fallers (NF) and 18 as older adults fallers (F). Table 1 shows mean (standard deviation) by group for basic demographic and anthropometric variables: age, height, weight and body mass index (BMI). Moreover, it shows the p-values obtained from a one-way ANOVA test. Importantly, no significant differences were found between groups NF and F, suggesting homogeneity between them with regards to age and basic anthropometric variables (thus discarding them as potential confounders).

Fig. 1 shows the mean and standard error of the mean by group for ApEn and SampEn values computed for m = {2, 3} and r = {0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5}. Lower mean entropies are observed for Y group compared to the NF/F groups for all combinations of *m* and *r*. The one-way ANOVA test revealed that those differences were statistically significant with a p-value<0.001 in all cases (thus not shown in this paper). Moreover, lower mean entropies can be observed for the NF group compared to the F group for all combinations of *m* and *r*. However, statistical testing revealed significant differences only for:

- ApEn(*m*=2, *r*={0.35, 0.4, 0.45}) and ApEn(*m*=3, *r*=0.5)
- SampEn(*m*=2, *r*={0.4, 0.45, 0.5}) and SampEn(*m*=3, *r*={0.15, 0.2})

Tables 2 and 3 show mean (standard deviation) by group for ApEn and SampEn, respectively, as well as p-values from the test of differences between NF and F.

Table 1. Subjects' basic demographic and anthropometric variables: mean (standard deviation) by group and p-values for a one-way ANOVA test.

Variable	Young (Y)	Non-Fallers (NF)	Fallers (F)	Y vs. NF	Y vs. F	NF vs. F
Age, years	27.72 (7.78)	71.54 (6.35)	71.20 (7.12)	**<0.001**	**<0.001**	0.984
Height, cm	166.81 (8.75)	157.77 (8.73)	155.19 (6.16)	**<0.001**	**<0.001**	0.502
Weight, kg	61.62 (7.73)	63.96 (8.43)	60.01 (8.10)	0.207	0.718	0.163
BMI, kg/m^2	22.20 (2.82)	25.71 (2.97)	24.88 (2.84)	**<0.001**	**0.001**	0.540

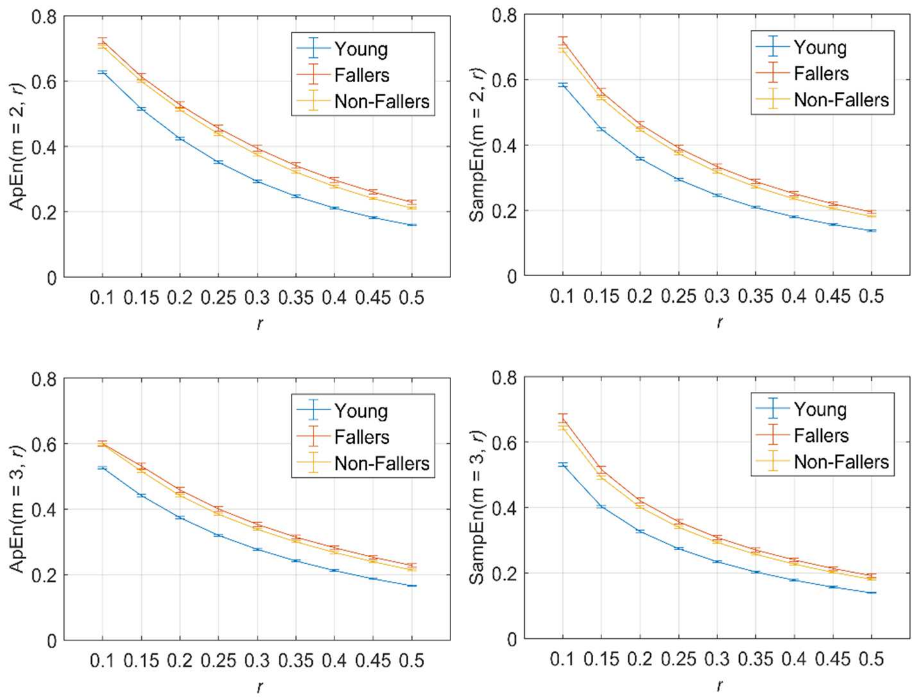

Fig. 1. Approximate Entropy (left) and Sample Entropy (right) for *m* = {2, 3} and *r* = {0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5}. Error bars represent the standard error of the mean.

4 Discussion and conclusions

The use of ApEn and SampEn to characterize the regularity of COP trajectories is an emerging practice in human balance research. While previous studies have achieved promising results regarding the use of those entropy measures to discriminate between groups and/or testing conditions, the adequate selection of input parameter values has been scarcely investigated. This study aimed (1) to determine correct input parameters for the computation of ApEn and SampEn for the analysis of COP time-series; and (2) to investigate the ability of ApEn and SampEn to discriminate between groups of young adults, and older adults with and without history of falls.

Overall, the results confirm that the selection of input parameters for the computation of entropy measures for COP time-series is a very critical for the discrimination between experimental groups. Certainly, our results suggest that ApEn and SampEn are able to discriminate with ease between two highly heterogeneous groups, e.g. young adults and older adults, for a wide range of *m* and *r* values. However, the choice of parameter values becomes crucial for the discrimination between groups that are closer to each other; e.g. older-adult non-fallers and older-adult fallers. Our current findings suggest that using combinations of *m*=2 and *r*={0.4,0.45} allows both ApEn and SampEn to discriminate between the latter.

Future studies should determine whether these entropy measures have a higher discriminative power under specific balance testing conditions (e.g. eyes open versus eyes closed) and whether it remains for shorter data lengths (e.g. N=600).

Table 2. Approximate Entropy: mean and standard deviation (SD) by group and p-value for a one-way ANOVA test.

	Young (Y)		Non-Fallers (NF)		Fallers (F)		NF vs. F
r	Mean	SD	Mean	SD	Mean	SD	p
m = 2							
0.1	0.628	0.129	0.705	0.108	0.723	0.138	0.178
0.15	0.515	0.134	0.599	0.104	0.613	0.131	0.298
0.2	0.424	0.136	0.512	0.110	0.527	0.133	0.280
0.25	0.351	0.131	0.438	0.113	0.455	0.133	0.176
0.3	0.293	0.121	0.374	0.110	0.394	0.129	0.093
0.35	0.247	0.109	0.321	0.104	0.341	0.122	**0.049**
0.4	0.211	0.098	0.277	0.096	0.297	0.113	**0.024**
0.45	0.182	0.087	0.241	0.087	0.260	0.104	**0.014**
0.5	0.159	0.077	0.211	0.079	0.229	0.094	0.009
m = 3							
0.1	0.526	0.109	0.597	0.094	0.600	0.114	0.939
0.15	0.441	0.113	0.516	0.103	0.531	0.128	0.170
0.2	0.374	0.106	0.441	0.093	0.459	0.117	0.080
0.25	0.320	0.099	0.384	0.085	0.400	0.107	0.073
0.3	0.277	0.094	0.338	0.081	0.353	0.099	0.088
0.35	0.242	0.089	0.300	0.078	0.314	0.094	0.084
0.4	0.212	0.084	0.267	0.075	0.282	0.089	0.064
0.45	0.187	0.078	0.239	0.072	0.253	0.084	0.057
0.5	0.166	0.073	0.214	0.068	0.228	0.079	**0.043**

Table 3. Sample Entropy: mean and standard deviation (SD) by group and p-value for a one-way ANOVA test.

	Young (Y)		Non-Fallers (NF)		Fallers (F)		NF vs. F
r	Mean	SD	Mean	SD	Mean	SD	p
m = 2							
0.1	0.583	0.158	0.689	0.140	0.718	0.179	0.051
0.15	0.447	0.136	0.542	0.116	0.562	0.146	0.125
0.2	0.358	0.124	0.445	0.109	0.463	0.133	0.149
0.25	0.294	0.113	0.373	0.102	0.390	0.123	0.116
0.3	0.245	0.101	0.316	0.095	0.333	0.114	0.082
0.35	0.208	0.090	0.271	0.087	0.288	0.104	0.058
0.4	0.179	0.080	0.235	0.079	0.250	0.095	**0.040**
0.45	0.156	0.071	0.205	0.071	0.220	0.085	**0.030**
0.5	0.137	0.063	0.181	0.064	0.194	0.077	**0.025**
m = 3							
0.1	0.531	0.163	0.643	0.156	0.672	0.199	0.064
0.15	0.403	0.125	0.491	0.120	0.515	0.152	**0.037**
0.2	0.327	0.106	0.401	0.098	0.421	0.124	**0.041**
0.25	0.274	0.094	0.339	0.085	0.356	0.107	0.051
0.3	0.234	0.085	0.294	0.077	0.308	0.096	0.069
0.35	0.203	0.078	0.257	0.071	0.270	0.087	0.073
0.4	0.178	0.071	0.227	0.066	0.240	0.080	0.066
0.45	0.157	0.066	0.202	0.062	0.214	0.074	0.061
0.5	0.139	0.060	0.181	0.058	0.192	0.069	0.053

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Conflict of interest statement

The authors declare that they have no conflict of interest.

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