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PII: S0167-9457(10)00058-8
DOI: 10.1016/j.humov.2010.04.005
Reference: HUMOV 1228

To appear in: *Human Movement Science*

Center-of-pressure regularity as a marker for attentional investment in postural control: a comparison between sitting and standing postures

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Acknowledgment

The authors are grateful to Dr. Schieppati for hosting the ISPGR satellite conference on "Basic mechanisms underlying balance control under static and dynamic conditions" in Pavia, and for editing this special issue. The contribution of PH was supported by the Czech Ministry of Education, Youth and Sports (grant no. RP 6198959221).

Abstract

Postural control is a highly automatized basic activity that requires limited attentional investments. These investments have been shown to increase from balancing experts to controls, and from controls to persons with impaired postural control. Such between-subject comparisons led to a proposed direct relation between the regularity of center-of-pressure (COP) fluctuations and the amount of attention invested in posture. This study aims to expand this relation to a within-subject comparison of conditions that differ in balance demands. Specifically, more regular COP fluctuations were expected for standing than sitting, as stimulus-response reaction-time studies showed that the required attentional demands are lower for sitting than standing. COP registrations were made for fifteen healthy adults in seated and standing postures. COP regularity was quantified with sample entropy. As expected, COP fluctuations were found to be more regular for standing than sitting, as evidenced by significantly lower sample entropy values. These findings expand the relation between COP regularity and the amount of attention invested in posture to postural tasks that vary in balance demands. An assessment of COP regularity may thus not only be instrumental in the examination of attentional investment in posture in between-subject designs, but also for different postures in within-subjects designs.

Keywords: postural control; attentional investment; center-of-pressure regularity; sitting; standing

1. Introduction

The control of everyday basic activities like sitting, standing, and walking is typically taken for granted. This is understandable from the fact that underlying control processes are largely autonomous and automatic, controlled without placing a substantial cognitive burden or attentional demand on the controller. Automaticity of control is functional as it allows for simultaneous performance and control of concurrent, commonly more attention-demanding tasks, such as talking to the phone, reading the newspaper, or holding a cup of coffee. Investigations using dual-task paradigms, however, made apparent that the control of abovementioned basic activities is not entirely automatic, but often requires attentional or cognitive resources (see Woollacott & Shumway-Cook, 2002, for a review). Several of those investigations used stimulus-response reaction times to operationalize attentional investment, which typically increased from sitting to standing to walking (e.g., Lajoie, Teasdale, Bard, & Fleury, 1993, 1996). The degree of cognitive investment also has been reported to vary with health status and expertise; attentional investment is typically greater for pathological groups than controls (e.g., Brown, Sleik, & Winder, 2002; stroke patients); Redfern, Talkowski, Jennings, & Furman, 2004; patients with unilateral vestibular loss), and smaller for experts than controls (e.g., Vuillerme & Nougier, 2004; gymnasts). This is particularly well-documented for postural control, revealing that performing secondary tasks while sitting or standing impacts upon either postural performance, secondary task performance, or both (cf. Fraizer & Mitra, 2008 for a review). Groups with impaired postural control (e.g., fall-prone elderly, stroke patients) are more affected by posture-cognition dual-tasking than controls (e.g., Brown et al., 2002; Huxhold, Li, Schmiedek, & Lindenberger, 2006; Lacour, Bernard-Demanze,

& Dumitrescu., 2008), whereas attentional effects in balancing experts (e.g., gymnasts, ballet dancers) have only been reported in more difficult postural configurations like standing on one leg (Stins, Michielsen, Roerdink, & Beek, 2009; Vuillerme & Nougier, 2004).

Interestingly, the dynamical structure of center-of-pressure (COP) profiles during quiet standing, in particular its regularity, was recently found to be positively related to the amount of attention invested in postural control (e.g., Donker, Ledebt, Roerdink, Savelsbergh, & Beek, 2008; Donker, Roerdink, Greven, & Beek, 2007; Roerdink et al., 2006; Stins et al., 2009). COP regularity can for example be computed by means of sample entropy, approximate entropy, and recurrence quantification analysis, yet –largely independent of differences in methodology– posturograms were found to be more regular in pathological groups than controls (e.g., Cavanaugh et al., 2006; Donker et al., 2008; Roerdink et al., 2006; Schmit et al., 2006), less regular in balance experts than controls (Schmit, Regis, & Riley, 2005; Stins et al., 2009), and less regular when attention was experimentally withdrawn from posture using secondary tasks (Cavanaugh, Mercer, & Stergiou, 2007; Donker et al., 2007; Roerdink et al., 2006; Stins et al., 2009). Clearly, the COP regularity findings for these between-subject and within-subject comparisons are congruent with the aforementioned stimulus-response results.

The purpose of the present experiment was to extend this line of research by comparing COP regularity between sitting and standing postures. To this end, we operationalized COP regularity in terms of sample entropy (see Methods for more details), a measure of time-series regularity developed by Richman and Moorman (2000). The balance demands required for sitting and standing postures differ considerably in mechanical terms, mainly because the center of mass is positioned closer to the base of support when seated (cf. Genthon & Rougier, 2006). As a consequence, adverse effects of internal or external perturbations are less pronounced in a seated position. Interestingly, numerous stimulus-response reaction-time studies showed that the attentional demand required for controlling a sitting posture is lower than that required for controlling a standing posture (Lajoie et al., 1993, 1996; Teasdale, Bard, LaRue, & Fleury, 1993; Vuillerme & Nougier, 2004; Vuillerme, Forestier, & Nougier, 2002; Vuillerme, Isableu, & Nougier 2006), which is at least to some extent related to the aforementioned mechanical difference in imposed balance demands between the two postures. Thus, in line with the proposed relation between COP regularity and the amount of attention invested in posture (Donker et al., 2007, 2008; Roerdink et al., 2006; Stins et al., 2009), we hypothesized that COP trajectories were more regular (lower sample entropy) for the standing than for the sitting posture, as the former posture is associated with a greater attentional investment (e.g., Lajoie et al., 1993, 1996; Teasdale et al., 1993; Vuillerme & Nougier, 2004; Vuillerme et al., 2002, 2006).

2. Methods

Participants. Fifteen healthy young male adults participated in the study (age (mean ± *SD*): 22 ± 1 years; body weight: 77 ± 5 kg; height: 178 ± 5 cm). They were naïve as to the purpose of the study. They gave their written informed consent to the experimental procedure as required by the Helsinki declaration and the local Ethics Committee. None of the subjects presented a history of motor problems, neurological disease, or visual or vestibular impairments.

Experimental procedure. Participants were asked to complete two postural conditions: sitting and standing. For the sitting task, participants were seated on a force platform (Equi+, PF01, Aix les Bains, France) positioned on a rigid table border 1 m above the floor with their back unsupported and the arms crossed over the abdomen. The proximal part of the thighs was supported by the force platform (i.e., distance between border of the force platform and the popliteus hollows corresponded to one-third of the thigh length) while the shanks and feet dangled unsupported (cf., Genthon & Rougier, 2006; Genthon, Vuillerme, Monnet, Petit, & Rougier, 2007). In the standing task, participants stood barefoot on the same force platform (now situated on the ground) in a natural position (feet abducted at 20°, heels 3 cm apart) with the arms hanging loosely at the sides. In both postural conditions, the healthy young participants had their eyes closed to reduce the likelihood of potential ceiling effects in attentional investments and/or COP regularity. Participants were instructed to minimize trunk and body motion for sitting and standing tasks, respectively. Trial duration was 32 s and anterior-posterior (AP) and medio-lateral (ML) COP trajectories were registered at a sampling rate of 64 Hz. The order of sitting and standing conditions was randomized over participants.

Data analysis. The AP and ML COP time series were linearly detrended and centered on zero mean prior in order to construct 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 AP and ML time series and is hence not sensitive to the orientation of the base of support with respect to force platform (Prieto, Myklebust, Hoffmann, Lovett, &

Myklebust, 1996). The "amount of sway" was quantified by means of two conventional, scale-dependent measures (see Prieto et al., 1996). First, the average COP distance to the origin of the mean-centered posturogram was determined by taking the mean of the RD time series (i.e., mean amplitude in mm). Second, path length (mm) was determined by taking the sum of the distances between consecutive points in the conventional posturogram (Prieto et al., 1996).

To examine the structure of COP trajectories in more detail, independent of its size or scale, two scale-independent COP measures were quantified. To this end, AP and ML time series were normalized to unit variance by dividing those time series by their respective standard deviations, resulting in a normalized posturogram. Subsequently, the path length of the normalized posturogram was determined in a similar manner as described above for the conventional posturogram. Since posturograms were normalized to unit variance, differences in path length could only be the result of changes in the structure of the posturogram, with a longer path in the normalized posturogram indicating a larger amount of "twisting and turning" or "curviness" in the COP trajectory (cf., Donker et al., 2007, 2008).

Second, sample entropy was quantified for RD distance time series and, in view of the potential non-stationary nature of COP trajectories (Ramdani, Seigle, Lagarde, Bouchara, & Bernard, 2009), also for RD increment time series. Both RD distance and increment time series were normalized to unit variance and algorithms of Lake and colleagues (Lake, Richman, Griffin, & Moorman, 2002; Richman, Lake, & Moorman, 2004) were used to estimate corresponding sample entropy values. Specifically, sample entropy is quantified as the negative natural logarithm of the conditional probability (CP

= A/B) that a dataset of length N, having repeated itself within a tolerance r for m points, will also repeat itself for $m + 1$ points, without allowing self-matches (see also Lake et al., 2002; Richman & Moorman, 2000). Accordingly, B represents the total number of matches of length m while A represents the subset of B that also matches for $m + 1$. Sample entropy thus follows from $-\log(A/B)$, with a low sample entropy value arising from a high probability of repeated template sequences in the data. In this context, entropy is the rate of generation of new information and the lower the entropy the greater the regularity of the time series in question.

Parameter choice of m and r was optimized to ensure that the number of matches remains large enough for reliable sample entropy estimation. Increased number of matches of length m and $m + 1$ (i.e., large B and A values) improve the accuracy and confidence of CP estimates, however, when m decreases and r increases (i.e., with relaxed criteria), the probability of matches tends toward 1 and sample entropy tends to 0, thereby loosing discriminative power. Thus, sample entropy is best estimated with m as large and r as small as possible. Lake and colleagues (2002) introduced a statistical criterion to optimize the parameter choice, which is based on the maximum of the relative error of sample entropy and CP estimates. This metric simultaneously penalizes CP near 0 and near 1 (Lake et al., 2002) and represents the tradeoff between accuracy and discriminative capability. The criterion was set to be no higher than .05, implying that the 95% confidence interval of the sample entropy estimate is maximally 10% of its value (Lake et al., 2002; see also Ramdani et al., 2009; Roerdink et al., 2006).

Statistics. To evaluate the effect of sitting and standing postures, the two conventional (i.e., mean amplitude and path length) and the two scale-independent (i.e., normalized path length and sample entropy) posturographic measures were subjected to separate two-tailed paired-samples *t*-tests. Sample entropy for both RD distance and increment time series were independently subjected to these *t*-tests. Bonferroni correction was applied in view of the number of comparisons (i.e., *p*-value of .05/5). Values are reported as mean ± *SD*.

3. Results

Fig. 1 depicts conventional and normalized posturograms (upper panels) and corresponding RD distance time series (lower panels) for sitting and standing postures of a single representative participant. As can be appreciated from this figure, the size of conventional posturograms differs markedly between sitting and standing postures (cf. two upper left panels), as evidenced by considerably smaller RD amplitudes for sitting than standing (lower left panel). As a consequence of this amplitude discrepancy, path length of the conventional posturogram is much shorter for sitting than standing postures. These typical findings are supported by groups statistics: 1) mean RD amplitude is significantly smaller for sitting than standing postures (0.57 ± 0.19 vs. 4.52 ± 1.29 mm, $t(14) = 12.37$, $p < .0001$) and, 2) path length of the conventional posturogram is significantly shorter for sitting than standing postures (159 ± 14 vs. 413 ± 62 mm, $t(14) = 16.67$, $p < .0001$).

-Fig. 1-

After normalization to unit variance, the size of the posturograms does not differ between sitting and standing postures (two upper right panels of Fig. 1); hence, mean RD amplitudes are comparable for normalized posturograms (lower right panel). Interestingly, in contrast to conventional posturograms, path length of normalized posturograms is considerably larger for sitting than standing postures, indicative of more "twisting and turning" or "curviness" in the posturograms. This was supported statistically as the path of normalized posturograms was found to be significantly longer for sitting than standing postures (428 ± 171 vs. 122 ± 31 a.u., $t(14) = 6.90$, $p < .0001$).

-Fig. 2-

Fig. 2 depicts the outcome of the parameter optimization procedure. As can be appreciated from this figure, the maximum template length for which the median of the relative error meets the 0.05 criterion is $m = 3$, irrespective of whether RD distance or RD increment time series are used. Corresponding optimal tolerance range values are 0.06 and 0.29, respectively (viz. minima in the $m = 3$ curves). Sample entropy was thus determined using $m = 3$ and $r = 0.06$ for RD distance time series and $m = 3$ and $r = 0.29$ for RD increment time series. As depicted in Fig. 3, sample entropy was larger for the sitting than for the standing posture for both RD distance (upper panels; 1.61 ± 0.22 vs. 0.62 ± 0.12; $t(14) = 20.39$, $p < .0001$) and RD increment (lower panels; 1.55 ± 0.07 vs. 1.17 ± 0.15; $t(14) = 8.29$, $p < .0001$) time series.

-Fig. 3-

4. Discussion

The aim of this study was to examine COP regularity in sitting and standing postures in a group of young healthy participants. In doing so, we attempted to expand the relation between COP regularity and the amount of attention invested in posture for conditions that differ in balance demands. Numerous stimulus-response reaction time studies disclosed greater attentional investments for standing than sitting postures, as evidenced by increased reaction times in the former posture (e.g., Lajoie et al., 1993, 1996; Teasdale et al., 1993; Vuillerme & Nougier, 2004; Vuillerme et al., 2002, 2006). Considering the proposed direct relation between COP regularity and the amount of attention invested in posture (Donker et al., 2007, 2008; Roerdink et al., 2006; Stins et al., 2009), and in line with abovementioned results, we expected more regular COP fluctuations for the standing than for the sitting posture. COP regularity was quantified by means of sample entropy and the results were fully in line with the expectations. Indeed, sample entropy was significantly lower (indexing more regular COP fluctuations) for the standing than for the sitting posture, independent of whether RD distance or RD increment time series were used (the latter was included in view of the potential non-stationarity of COP time series during standing, cf. Ramdani et al., 2009). Moreover, conventional posturographic measures showed greater COP displacements for standing than sitting postures, as evidenced by significantly larger RD amplitude and path length. These conventional COP measures were complemented by the path length of the normalized posturogram (cf. Donker et al., 2007, 2008) to index the amount of "twisting and turning" or "curviness" in the posturogram, independent of its size. The results were opposite to path lengths for conventional posturograms; the path of the normalized posturogram was longer for sitting than standing postures (Fig. 1), symptomatic of more “complex” posturograms in the former postural configuration. This observation is clearly in line with the more irregular posturograms for sitting than standing postures, as evidenced by higher sample entropy (Fig. 3), which is also a scale-independent measure.

On the whole, these results support the proposed relation between COP regularity and the amount of attention invested in posture (cf. Donker et al., 2007, 2008; Roerdink et al., 2006; Stins et al., 2009). Moreover, the results expand this relation to postural tasks that vary in balance demands. To date, evidence in favor of the COP-regularity / attentional-investment relation stemmed primarily from between-subject comparisons, in which COP regularity was compared between controls and experts (e.g., ballet dancers; Schmit et al., 2005; Stins et al., 2009), or between controls and patients (e.g., stroke patients, children with cerebral palsy, Parkinson’s patients, athletes with cerebral concussion; Cavanaugh et al., 2006; Donker et al., 2008; Roerdink et al., 2006; Roerdink, Geurts, de Haart, & Beek, 2009; Schmit et al., 2006). Recently, the relation was further validated by studies adopting a within-subject design with and without diverting attention experimentally from posture by means of a dual task (Cavanaugh et al., 2007; Donker et al., 2007; Roerdink et al., 2006; Stins et al., 2009). Moreover, a few longitudinal studies on clinical posturography showed that COP fluctuations become increasingly more irregular in the course of rehabilitation after stroke (Roerdink et al., 2006) or cerebral concussion (Cavanaugh et al., 2006), which is in line with the clinical observation that with recovery the control of posture becomes less attention demanding (cf. Geurts, de Haart, van Nes, & Duysens, 2005, for a review on the recovery of posture after stroke).

With the present study, the relation between COP regularity and the amount of attention invested in posture was further corroborated by results arising from a within-subject design with different imposed balance demands acting on the postural task (control of sitting vs. standing postures). Hence, COP regularity may tentatively not only be employed as a measure to index differences in the amount of attention invested in posture between different groups of participants or with recovery during rehabilitation, but also between different postures within a group of participants. This expansion of the relation between COP regularity and the amount of attention invested in posture could have potential relevance for clinical posturography. That is, in rehabilitation settings the amount of attention invested in the control of upright quiet stance under different base of support configurations (i.e., standing with the feet apart, with the feet together, or in tandem stance) may possibly be evaluated simply by examining COP regularity. Nevertheless, future studies are first required to validate the use of sample entropy as a marker of the amount of attention invested in posture against a gold standard stemming from stimulus-response reaction time tasks. In addition, the question which marker (i.e., sample entropy vs. stimulus-response reaction time) is most sensitive and reliable in the evaluation of the amount of attention invested in posture needs to be addressed prior to widespread application of sample entropy in clinical posturography.

Ramdani and colleagues (2009) recently proposed to apply sample entropy analyses to COP increment time series rather than the raw position time series in view of the possible non-stationary nature of the latter due to long-range correlations. Indeed, Govindan, Wilson, Eswaran, Lowery, and Preißl (2007) showed that such correlations may lead to difficulties in the correct quantification of the underlying complexity of the system. Such difficulties can be circumvented by taking the first difference of COP time series, as temporal correlations are minimized in increment time series of long-range correlated processes (Govindan et al., 2007; Ramdani et al., 2009). In the present study, sample entropy was therefore determined for both RD distance and RD increment time series, with qualitatively similar results; in both cases sample entropy was significantly larger for sitting than standing posture (Fig. 3). In contrast, Ramdani et al. (2009) reported a significant difference in sample entropy between conditions of standing with eyes open and standing with eyes closed for the COP increment time series only. The insignificant result for original COP time series may well be due to the fact that the parameter optimization procedure was applied only for the increment data (resulting in $m = 3$ and $r = 0.30$, which is comparable to our optimal values distilled from Fig. 2). For original COP time series, Ramdani and colleagues determined sample entropy with "classical parameters $m = 2, 3$ and $r = 0.20$", which, as can be appreciated from Fig. 2, are far from suitable. In fact, parameter optimalization as applied in our study (cf. Fig. 2) and in previous studies consistently led to r values ranging between 0.035 and 0.06 (Donker et al., 2007, 2008; Roerdink et al., 2006, 2009; Stins et al., 2009). The liberal choice of $r = 0.20$ may thus have reduced the discriminative power of sample entropy estimates considerably, as confirmed by the fairly low sample entropy values of about 0.15 (cf. Table B1 in Ramdani et al., 2009, p. 1030), implying that the conditional probability of finding matches progresses towards 1.

This faux pas notwithstanding, Ramdani and colleagues (2009) are consistent with other studies demonstrating the potential of sample entropy, or regularity statistics in general, to characterize complexity features in posturograms, by concluding that, with appropriate *m* and *r* parameters, "sample entropy could be a good dynamical signature to characterize the postural effects of aging and diseases" (p. 1029). We fully endorse this conclusion and would like to add that COP regularity, so-defined, may represent a marker of the amount of attention invested in the control of posture, between groups that differ in age, health status, or expertise, as well as within groups, under changing postural demands, as outlined in Fig. 4. In this figure, the relation between COP regularity and the amount of attention invested in posture is summarized using a COP-regularity continuum in parallel to an automaticity-of-control continuum (Panel A). That is, based on regularity characteristics of posturograms, the former continuum ranges from fairly regular (left side) to fairly irregular posturograms (right side). Based on reaction times found in stimulus-response paradigms during postural control, the latter continuum ranges from low automaticity of control (large reaction times, left side) to highly automatized control (short reaction times, right side). As is often the case with a continuum, controls are situated somewhere in the centre, whereas "pathology" and "expertise" are located at left and right sides, respectively (Panel B). There are several within-subject factors influencing the relative position in the parallel continua (Panel C). That is, with recovery from pathology, the position in the continuum progressively shifts towards the right. If attention is experimentally withdrawn from posture, the position in the continuum shifts towards the right as well. As demonstrated in the present study, the position in the parallel continua depends on the imposed balance demands (towards the right side with less challenging demands, e.g., sitting instead of standing). The same holds for imposed postural threats (towards the left side when standing at the edge of a cliff, cf. Huffman, Horslen, Carpenter, & Adkin, 2009; Stins et al., 2010) and imposed sensory deprivation (towards the left side when standing with eyes closed vs. standing with eyes open; Donker et al., 2007; Ramdani et al., 2009).

-Fig. 4-

There are several unexplored paths in the parallel continua to further verify or falsify the proposed relation between COP regularity and the automaticity of control. Examples are adopting an internal vs. external attentional focus (e.g., McNevin & Wulf, 2002; Vuillerme & Nafati, 2007), gradually diverting larger amounts of attention from posture (e.g., Pellecchia, 2003; Riley, Baker, & Schmit, 2003; Swan, Otani, & Loubert, 2007; Vuillerme et al., 2000, 2006), healthy ageing (e.g., Huxhold et al., 2006; Lacour et al., 2008), a comparison between normal and fatigued standing (e.g., Vuillerme et al., 2002), et cetera. Ideally, future studies in this direction should adopt a complementary approach by studying both COP regularity from posturograms and the attentional investment in posture from stimulus-response reaction-time paradigms. The limitation of the proposed relation between COP regularity and the amount of attention invested in posture currently resides in the question *why* the regularity of COP trajectories would change with changes in the degree of automaticity of postural control, in other words, what are the mechanisms underlying the existing link between COP regularity and attentional investment in posture? Future efforts are required to uncover underlying control processes responsible for the proposed relation. This limitation notwithstanding, based on the present set of converging findings, as summarized in Fig. 4, and pending consistent findings of recommended future studies for the unexplored paths in the parallel continua, we feel confident by stating that regularity of COP fluctuations may be considered as a marker for the amount of attention invested in posture.

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Fig. 1. Conventional and normalized posturograms of a single participant for sitting and standing postures (upper panels), as well as corresponding RD distance time series (lower panels). Respective path lengths and RD amplitudes are indicated as well; see text for further details.

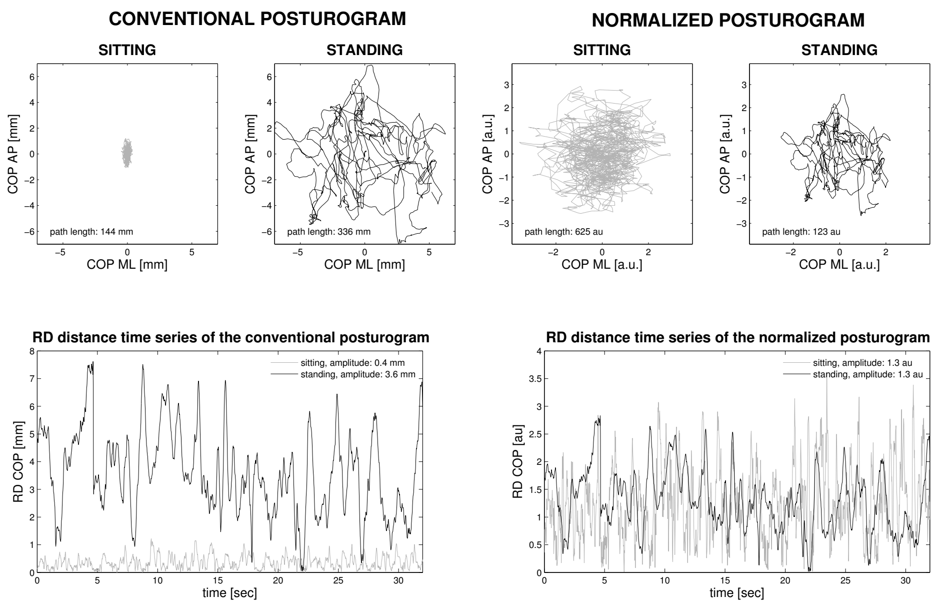

Fig. 2. A visual guide to optimal selection of template length *m* and tolerance range *r* for sample entropy estimation of RD distance and RD increment time series, using a criterion value of 0.05 for the median of the maximal relative in CP and sample entropy estimates (upper panels). The lower panels depict corresponding sample entropy values for various combinations of *m* and *r*, showing convergence for *m* is 2 to 4. Note that the depicted maximum relative error (upper panels) and sample entropy (lower panels) plots for the various parameter combinations represent median curves for all trials of all participants.

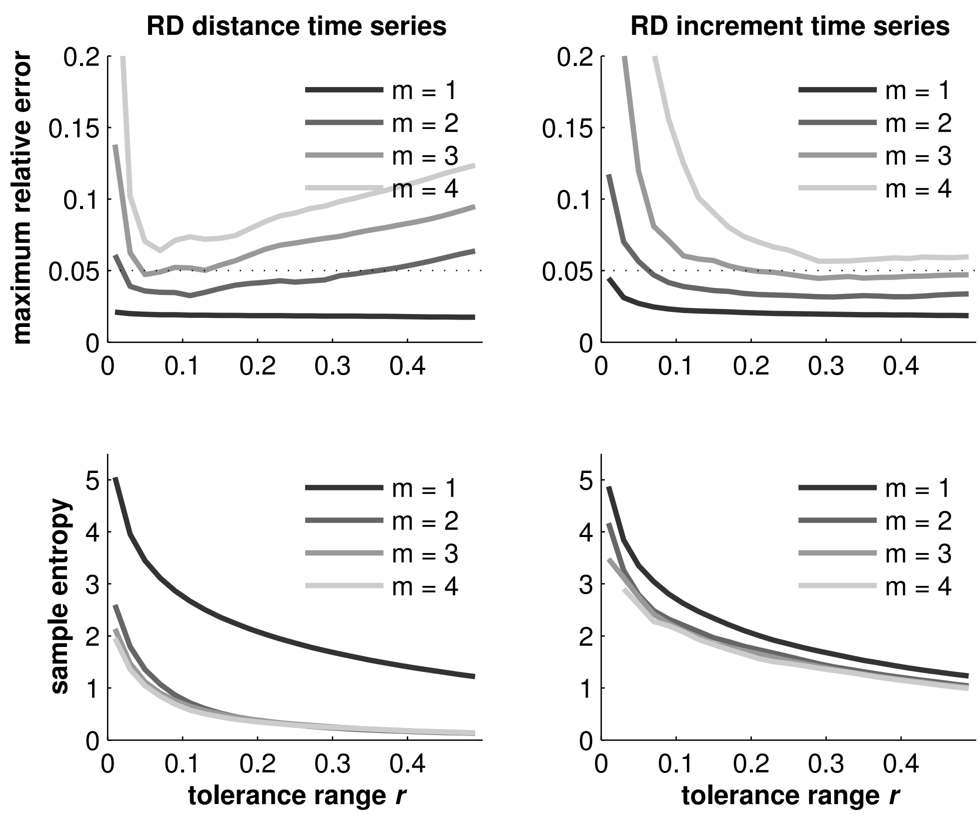

Fig. 3. Typical sitting (gray) and standing (black) RD distance (upper left panel) and RD increment (lower left panel) time series, with associated sample entropy values indicated in the legend. Average sample entropy values for these conditions collapsed over all participants are depicted in the panels on the right.

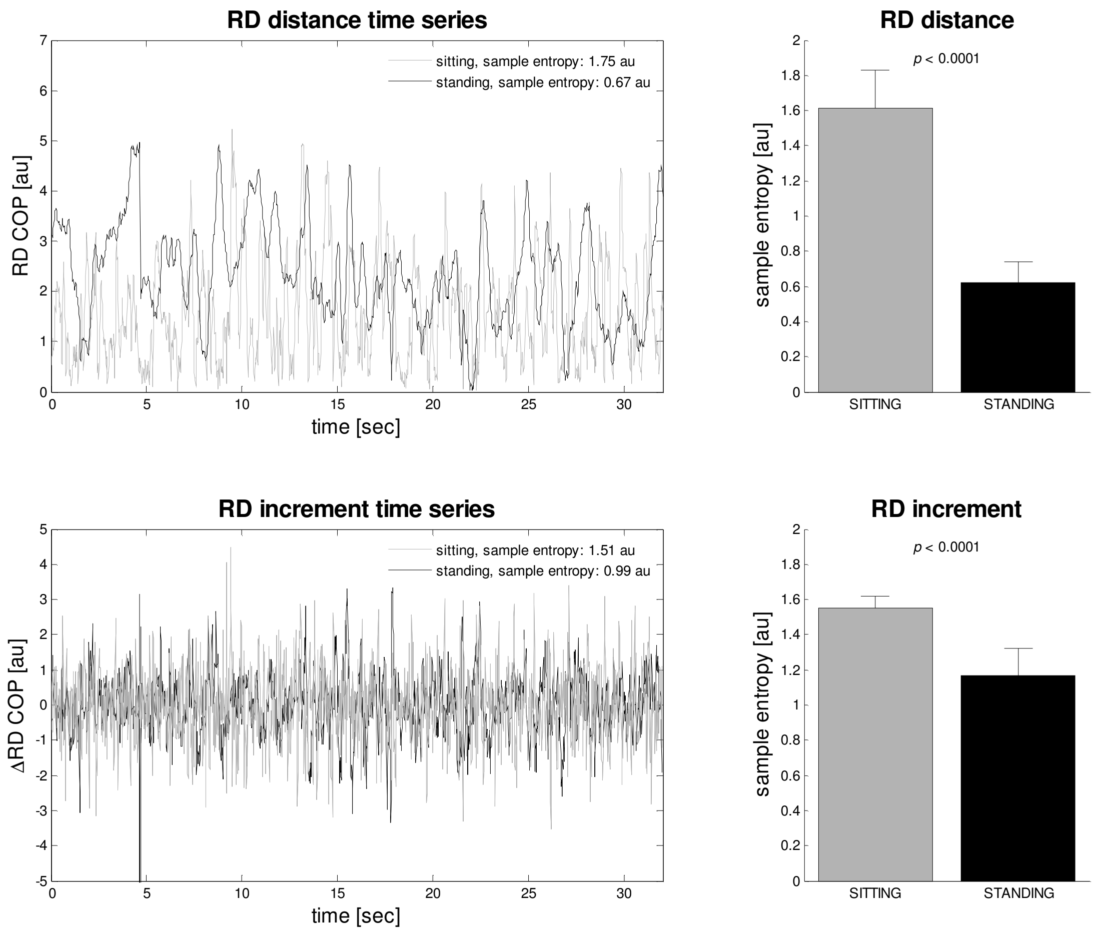

Fig. 4. Schematic overview of the relation between COP regularity and automaticity of control, represented as parallel continua with relatively regular posturograms and lower automaticity of postural control on the left, and relatively irregular posturograms and higher automaticity of control on the right hand side of the figure (A). Between-subject and within-subject factors influencing the relative position within the continua are indicated in panels B and C, respectively (see text for details).