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An entropy approach for evaluating adaptive motor learning processes while walking with unstable footwear

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ABSTRACT

This study evaluated the short- and long-term effects of unstable shoes (US) on the structure/shape of variability in gait. Therefore, sample entropy (SEn) values of centre of mass velocity (vCOM) signals in medio-lateral (ML), anterior-posterior (AP) and vertical (VT) direction were computed for 12 sport students during walking with US and flat shoes (FS) before and after a 10-week accommodation period. Statistical analysis included two-way repeated-measures ANOVA followed by *post hoc* tests where appropriate ($\alpha = 0.05$). Most noteworthy, it was found that (1) when compared to FS, using US increased the predictability of vCOM time series, not necessarily always at pre-test, but especially at post-test since (2) the corresponding SEn values decreased for the US condition while remaining stable for the FS condition during the interval between laboratory visits, although (3) the related shoe-by-visit interaction effects were only significant for vCOM_{ML} data and not for vCOM_{AP} nor for vCOM_{VT} data. Accordingly, the path of adapting to US was characterised by a “decomplexification” of the motor system; however, the variable practice (i.e., training) loads accompanying such a footwear intervention were probably too small to further expand the overall flexibility capabilities of athletically active persons (in more real-life settings).

1. Introduction

Unstable shoes (US) were originally constructed with the intention of providing an easy and inexpensive device for training leg strength and proprioception of users as they went about the routine tasks of daily living (Nigg, Hintzen, & Ferber, 2006). Indeed, there is ample evidence in the literature that supports the main idea of US physically guiding an improvement in global muscle function, while other frequently reported benefits (e.g., increased blood flow, energy expenditure and balance skills or reduced pain and joint loading) accompanying such a footwear intervention were usually supposed to be a direct consequence, thereof (Maffiuletti, 2012; Nigg, Baltich, Federolf, Manz, & Nigg, 2017; Papalia et al., 2015). Yet, to look beyond this conventional interpretation of the effects of US, their specific design concept was additionally examined for the role of movement variability in defining overall motor expertise, with the work of Stöggl, Haudum, Birklbauer, Murrer, and Müller (2010) being presumably the most noteworthy.

Briefly, Stöggl et al. (2010) compared standard deviation (SD) values of consecutive gait cycles in various discrete biomechanical variables (e.g., peak foot forces, mean joint angles, etc.) between walking with flat shoes (FS) and US before and after a 10-week

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accommodation phase. The authors discovered that the initially larger extent of variability within the US condition consistently decreased to nearly normal levels with practise, whereas the extent of variability within the FS condition remained quite constant during the interval between laboratory visits. Hence, US were said to serve as an external constraint for promoting certain aspects of dynamic stability, even though conflicts of transferability into more real-life settings existed (i.e., the absence of a training effect). Stöggl and Müller (2012) came to a similar conclusion in a subsequent follow-up study, as did Landry, Nigg, and Tecante (2010) and Ramstrand, Thuesen, Nielsen, and Rusaw (2010) with regard to static stability issues.

Referring to contemporary models on the nature and complexity of movement system variability as it relates to health and motor development (Davids, Glazier, Araújo, & Bartlett, 2003; Lipsitz, 2002; Newell & James, 2008; Stergiou & Decker, 2011), all of the previously listed longitudinal trials conducted in the field of US seemingly suffer from the limitation of only having implemented traditional measures of dispersion (e.g., SD, variance, etc.). Although these procedures are obviously able to determine the magnitude/amount of variability in signal output, that is, the outcome of performance, the corresponding structure/shape of variability, which represents the central organisation of movement patterns, may be more appropriately unfolded by so-called "nonlinear" tools (Stergiou & Decker, 2011). Since both approaches explore different facets of variability, neither should be ignored; however, citing Glazier and Davids (2009, e2) "it is the *structure*, rather than the *magnitude*, of movement variability that appears to be of greater significance in understanding normal and pathological human perceptual-motor functioning".

Methods elaborated for extracting the relevant dynamics of physiological time series include, just to name a few (out of dozens), detrended fluctuation analysis, wavelet transform modulus maxima, largest Lyapunov exponent, recurrence quantification analysis, or spectral and fuzzy entropy (Tang, Lv, Yang, & Yu, 2015). Nevertheless, the sample entropy (SEn) algorithm is probably still the most often utilised technique for this purpose (Anderson & Button, 2017; Tang et al., 2015), intuitively, due to (1) the presence of detailed guidelines for its input parameter selection (Lake, Richman, Griffin, & Moorman, 2002; Ramdani, Seigle, Lagarde, Bouchara, & Bernard, 2009), (2) its accuracy when evaluating short (experimental) records (Richman & Moorman, 2000), and (3) its relatively low computational efforts (Tang et al., 2015). Basically, estimators of SEn quantify the predictability (i.e., regularity, repeatability or orderliness) of a sequence of numbers and as such, but not without some controversy (e.g., Goldberger, Peng, & Lipsitz, 2002), can reveal helpful insights into the complexity of oscillations produced by the (motor) system (Richman & Moorman, 2000). Currently widely accepted (Harrison & Stergiou, 2015), complex variations in human motion are indicative of a rich repertoire of coordinative strategies, which allow the controller to readily respond to the stresses of an ever-changing environment. Numerically, this dexterity, known as motor flexibility, is generally associated with higher SEn values, or in other words, with the variability in task execution becoming more irregular, such as typically seen in expert performers (Lamoth & van Heuvelen, 2012; Preatoni, Ferrario, Donà, Hamill, & Rodano, 2010; Stins, Michielsen, Roerdink, & Beek, 2009).

Interestingly, learning to maintain a homeostatic equilibrium on unstable surfaces was commonly found to cause a decline of movement complexity reflected as rigidity (Ko, Challis, & Newell, 2003; Lamoth, van Lummel, & Beek, 2009; Strang, Haworth, Hieronymus, Walsh, & Smart, 2011). For example, over the course of mastering standing on foam mats, Strang et al. (2011) noticed a continuous reduction of SEn values of centre of pressure fluctuations in young pain-free adults. This is explainable by the fact that training devices like foam mats or "wobbling" boards introduce more degrees of freedom (DOF) to the dynamics of the system (Ko et al., 2003). Consequently, the much stronger compression of DOF into lower-dimensional (i.e., less complex) functional synergies in case of such increased task demands is reasonable when considering that the solution to a (movement) "problem" must always be simpler than the (movement) "problem" itself (Newell, Broderick, Deutsch, & Slifkin, 2003). If true, larger entropy values of biological signals in the early stage of motor learning can, therefore, not be read as a sign of greater flexibility, but rather as a sign of the learner exploratively searching for alternative metastable regions in the available perceptual-motor landscape (Barbado Murillo, Sabido Solana, Vera-Garcia, Gusi Fuertes, & Moreno, 2012; Newell & James, 2008). Further, during adaptation to challenging (unstable) task conditions, individuals enhance their attunement to sensory information for action (through experience) resulting in a broader responsiveness of their processes governing movement (Davids et al., 2003; Nigg et al., 2017; Stergiou & Decker, 2011). Thus, the recently detected findings of instability resistance training programmes leading to more complex (i.e., less predictable) patterns of coordination in otherwise unconstrained movement settings (e.g., stable surface) – once they had been completed (Huisinga, Filipi, & Stergiou, 2012; Menayo, Encarnación, Gea, & Marcos, 2014; Roerdink et al., 2006) – are plausible, as well.

Unsurprisingly, using US was shown to initiate a "decomplexification" of gait and posture variability in able-bodied subjects, who were already familiar with this unique type of footwear (Buchecker, Wegenkittl, Stöggl, & Müller, 2018; Federolf, Tecante, & Nigg, 2012; Federolf, Zandiyeh, & von Tscharner, 2015). However, none of these experiments employing nonlinear measures featured a pre-post-test protocol. Accordingly, to date, it is unclear if or how "exercising" with US temporally influences the underlying adaptation mechanisms of wearers, and whether transfer effects to the normal FS condition would occur.

In light of the above, the aim of this study was to re-analyse the original kinematic gait data of Stöggl et al. (2010) and Stöggl and Müller (2012), respectively, from a complexity sciences perspective by means of the SEn approach. The hypotheses tested were that (1) system complexity decreases from pre- to post-test for the US condition, (2) system complexity is lower when walking with US compared to FS, in particular at post-test, and (3) system complexity increases over time when walking with FS.

2. Methods

As stated before, this study utilised the raw data of two previously conducted investigations (Stöggl et al., 2010; Stöggl & Müller, 2012), which were obtained within the same methodological framework, as briefly described below. Nevertheless, in view of the nonlinear analysis background of the present work, the experimental tools applied here, including most of the data pre-processing techniques, are different to those initially reported (Stöggl et al., 2010; Stöggl & Müller, 2012).