A summary of the doctoral dissertation "Reinterpretation of variability of gait spatio-temporal parameters"

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Humans seamlessly modify their gait to carry out concurrent tasks or to cope with changing environmental conditions. They can, for example, adjust speed, foot clearance, the base of support, or execute arm and torso movements. Interestingly enough, stride length (SL), stride time (ST), and stride speed (SS) do fluctuate during undemanding straight-line walks on a level surface or even during treadmill walking. Gait fluctuations attracted general interest forty years ago, but the first empirical studies on variability in movement execution were conducted much earlier, at the end of the 19th century. It is surprising that the analysis of such variability profoundly changed the understanding of motor control and skill learning.

Until the turn of the century, fluctuations of spatio-temporal gait parameters (ST/SL/SS) of approximately 3–4% were treated as an uncorrelated random process. In 1995, Hausdorff et al. discovered long-range, persistent correlations in ST. Their choice of fractional Brownian motion for modeling such correlations has significantly influenced how ST/SL/SS variability was subsequently quantified and interpreted. In their original study, Hausdorff et al. applied detrended fluctuation analysis (DFA) to estimate the scaling (Hurst) exponent, which characterizes the properties of fractal time series. Over the last quarter-century, this was the method of choice for analyzing the scaling properties of gait time series in particular and physiological signals in general. The DFA assumes the time series as the superposition of two independent contributions: the polynomial trend and the signal with null covariance. However, the outcome of DFA does not by itself allow for the validation of the decomposition assumption. For the most part, researchers disregarded this problem. For example, there has been a consensus in the gait analysis community that ST time series is made up of persistent (scaling exponent greater than 0.5) fractal fluctuations superposed on trends that are irrelevant from the point of view of fractal analysis.

In DFA, a signal is divided into analyzing windows of different sizes in which a trend (a polynomial of a priori chosen order) is removed. Partitioning the signal into a set of nonoverlapping windows and performing detrending in a window-based manner does not guarantee that the functional form of the trend in each window is identical to the assumed one. In this thesis, rather than relying on the very specific form of a detrending characteristic of DFA, I adopted Multivariate Adaptive Regression Splines (MARS) to explicitly determine trends in spatio-temporal gait parameters during treadmill walking. Then, I used DFA and the madogram estimator to calculate the scaling exponent of the corresponding MARS residuals. I found that the duration of ST and SL trends were independent of treadmill speed and had distributions with exponential tails. At all speeds considered, the trends of ST and SL were strongly correlated and statistically independent of their corresponding residuals. The averages of scaling exponents of ST and SL MARS residuals were slightly smaller than 0.5. Thus, contrary to the interpretation prevalent in the literature, the statistical properties of ST and SL time series originate from the superposition of large-scale trends and small-scale fluctuations. Trends serve as the control manifolds about which ST and SL fluctuate. Moreover, the trend speed, defined as the ratio of instantaneous values of SL and ST trends, is tightly controlled about the treadmill speed. The strong coupling between the ST and SL trends ensures that the concomitant changes of their values correspond to movement along the constant speed goal equivalent manifold. This coupling is an automatic way of controlling gait speed and manifests the minimum intervention character of human motor control. At normal and moderate treadmill speeds, in the presence of random belt speed perturbations, strongly anti-persistent fluctuations about gentle, persistent trends can lead to weak persistence/antipersistence of ST/SL time series.

Optimization of energy cost determines the ST/SL/SS average. However, humans need to continuously adjust these parameters to respond to exogenous and endogenic perturbations during walking. While some neurological mechanisms that trigger these responses are known, our understanding of the fundamental principles governing step-by-step adaptation remains elusive. For example, to stay on a treadmill, the subject's step duration and length must yield a step speed that can fluctuate over a narrow range centered on the treadmill belt's speed. The results of previous experiments with walking on a split-belt treadmill underscore the intricacies of such aggregation. In particular, spatial and temporal controls of locomotion are accessible through distinct neural circuits, and neural control of intra- versus interlimb parameters (calculated using values from both legs, e.g., step length, double support) during walking is to a large extent independent. I investigated the ST/SL/SS time series dynamics following a sudden, large deviation from the mean value. In particular, I demonstrated that whenever the value of a gait parameter was markedly greater (smaller) than the mean value, it was either immediately followed by a smaller (greater) value of the contralateral leg (interleg control) or the deviation from the mean value decreased during the next movement of the ipsilateral leg (intraleg control). In other words, treadmill walking errors are not gradually attenuated via long-term corrections but are corrected immediately by the same or opposite leg. I found that the short-term control of gait spatio-temporal parameters for subjects with right foot preference was stronger for the right leg.

The fundamental problem, which has not yet been investigated, concerns the contribution of SL and ST fluctuations to SS variability. Therefore, I approximated SS variance by the linear combination of SL variance, ST variance, and SL-ST covariance. Then, I used it to elucidate gait control on a treadmill whose belt speed is perturbed by a strong, high-frequency noise – the simplest model of continuous gait adjustment. The combination coefficients are nonlinear functions of ST and SL mean values and, consequently, are speed dependent. The approximation applies to unperturbed and perturbed walking. In the first case, up to 80% of SS variance comes from SL fluctuations. In the presence of perturbations, the SL contribution decreases with increasing speed and noise amplitude. However, its lowest value is still twice as large as that of either ST variance or SL-ST covariance. The presented evidence shows that SL adjustments are primarily responsible for speed maintenance during walking. Such a control strategy is advantageous due to the weak speed dependence of the SL contribution to SS variance.

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27.09.2021