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Walking at the preferred stride frequency maximizes local dynamic stability of knee motion

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ABSTRACT

Healthy humans display a preference for walking at a stride frequency dependent on the inertial properties of their legs. Walking at preferred stride frequency (PSF) is predicted to maximize local dynamic stability, whereby sensitivity to intrinsic perturbations arising from natural variability inherent in biological motion is minimized. Previous studies testing this prediction have employed different variability measures, but none have directly quantified local dynamic stability by computing maximum finite-time Lyapunov exponent (λ^{Max}), which quantifies the rate of divergence of nearby trajectories in state space. Here, ten healthy adults walked 45 m overground while sagittal motion of both knees was recorded via electrogoniometers. An auditory metronome prescribed 7 different frequencies relative to each individual's PSF (PSF; ± 5, ± 10, ± 15 strides/min). Stride frequencies were performed under both freely adopted speed (FS) and controlled speed (CS: set at the speed of PSF trials) conditions. Local dynamic stability was maximal (λ^{Max} was minimal) at the PSF, becoming less stable for higher and lower stride frequencies. This occurred under both FS and CS conditions, although controlling speed further reduced local dynamic stability at non-preferred stride frequencies. In contrast, measures of variability revealed effects of stride frequency and speed conditions that were distinct from λ^{Max}. In particular, movement regularity computed by approximate entropy (ApEn) increased for slower walking speeds, appearing to depend on speed rather than stride frequency. The cadence freely adopted by humans has the benefit of maximizing local dynamic stability, which can be interpreted as humans tuning to their resonant frequency of walking.

1. Introduction

Humans can accommodate a wide range of walking speeds and stride frequencies, yet display consistent individual preferences. Knowledge about why these particular gait parameter values are adopted in healthy individuals promises to help us understand changes to gait with aging and disease. The preferred stride frequency (PSF) for healthy children and young adults can be estimated from modeling the legs as a single pendulum with spring attachment, and computing the resonant frequency of the model for equal gravitational (pendulum) and elastic (spring) moments (Holt et al., 1990; Holt et al., 1991b). Further evidence that PSF can be understood as moving at resonance comes from finding that, for a given speed, the propulsive force provided by the gastrocnemius muscle (Winter, 1983) and overall oxygen consumption are minimal at PSF (Holt et al., 1990, 1991b; Russell and Brillhart, 2005). Moving at resonance is also expected to maximize local dynamic stability, where fluctuations are minimized and intrinsic perturbations arising from natural variation are quickly damped out (Goodman et al., 2000; Holt et al., 1995; Rosenblum and Turvey, 1988). Greater smoothness in the acceleration profiles of the head and pelvis during walking at PSF, as quantified by harmonic ratios, provides indirect evidence for this prediction (Latt et al., 2008). More generally it has been hypothesized that freely chosen movement patterns have minimal variability (Danion et al., 2003). However, measures which quantify stride or coordination variability have revealed minima at different cadences that do not all correspond with PSF (Danion et al., 2003; Holt et al., 1995).

Mixed findings may stem from assuming that variability is the inverse of dynamic stability (Dingwell et al., 2001). Variability is typically quantified via the standard deviation (SD) or coefficient of variation (CV) of parameters, which provide a time independent measure of the amount of variation. This ignores the time sensitive changes in a movement trajectory. Local dynamic stability can be thought instead to represent the ability of a movement system to rapidly reduce deviations in its state space. For example, small natural variations in motion of the knee during a gait cycle can

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grow over time (less dynamically stable) or be constrained (more dynamically stable). Local dynamic stability can be best assessed by the maximum finite-time Lyapunov exponent (λ^{Max}) which directly quantifies the rate of divergence of nearby points in state space (Dingwell et al., 2001; England and Granata, 2007). Distinct patterns of results between measures of variability and stability emphasize that they quantify different characteristics of gait (Bruijn et al., 2009; Dingwell et al., 2001; Terrier and Dériaz, 2011). Given also that λ^{Max} has high validity for quantifying gait stability and predicting fall risk (Bruijn et al., 2013), this study computed λ^{Max} on individuals walking at different stride frequencies.

Treadmills have typically been employed in studies of local dynamic stability to provide long walking trials needed to compute λ^{Max}. However, use of a treadmill leads to more dynamically stable gait (Dingwell et al., 2001; Terrier and Dériaz, 2011), likely influenced by the constancy of the belt speed. Our goal of understanding the freely chosen walking cadence under natural conditions, without the driving influence of a treadmill, necessitated the investigation of overground gait. As gait initiation, termination or changes in direction would influence λ^{Max}, participants walked along a long, straight, flat path without any obstacles and the starting and ending strides were ignored.

The primary goal of this study was to determine if walking overground at the PSF maximizes local dynamic stability by having participants walk at seven different stride frequencies relative to their PSF. Given that individual PSF's have been estimated by a hybrid pendulum-spring model of the legs (Holt et al., 1990; Holt et al., 1991b) we expect that the local dynamic stability benefits will be detected in the motion of the legs. Previous research has shown consistent λ^{Max} findings across different joints (Dingwell et al., 2001; England and Granata, 2007), hence knee sagittal plane motion was selected to be recorded using electrogoniometers. Additionally though, altering stride frequency leads to changes in walking speed, which in turn influences λ^{Max} (Bruijn et al., 2009; Buzzi and Ulrich, 2004; Dingwell and Marin, 2006; England and Granata, 2007). In an effort to distinguish frequency from speed effects, participants performed the seven stride frequencies both at their freely adopted speed and within $\pm 10\%$ of their preferred walking speed. Moving at PSF or resonant frequency is also expected to maximize the predictability of motion (Goodman et al., 2000), which can be accessed via approximate entropy (ApEn), computed as the probability of vectors in a time series repeating (Pincus, 1991). Other time independent measures of variability were also computed to determine whether they had the same cadence effects as λ^{Max}.

2. Methods

2.1. Subjects

Six men and four women, with no known musculoskeletal or neurological problems, volunteered to participate [mean age 21.1 years (SD 2.3), mean height 1.75 m (0.09), mean body mass 75.8 kg (14.3)]. Anthropometric measurements and the estimated hybrid pendulum-spring model resonant frequencies are provided in supplementary material. All participants gave informed consent in accordance with the Pennsylvania State University Institutional Review Board.

2.2. Apparatus

Participants walked along a straight 45.30 m walkway. Sagittal plane knee motion was recorded using two electrogoniometers with an accuracy of $\pm 2^\circ$ over a 90° range from neutral and a repeatability of $< 1^\circ$ (SG 150, Biometrics Ltd, Cwmfelinfach, United Kingdom). The electrogoniometers were attached over the lateral side of both knees using double sided tape, and secured with underwrap and athletic tape. Data was recorded at 100 Hz (DataLINK, Biometrics Ltd, Cwmfelinfach, United Kingdom). Average speed was computed from timing gates (Brower Timing Systems, Draper, UT, Model Speed Trap II). An auditory metronome (DM50S, Seiko Sports Life Co., Tokyo, Japan) clipped to the participant's clothing prescribed the stride frequency.

2.3. Tasks and procedures

Electrogoniometers were attached and calibrated using a goniometer with each knee held in peak extension and 90° flexion. Each participant performed two practice trials under the instruction to: "Walk comfortably at your preferred speed". Participants had 3 m before and after the walkway to speed up and slow down. After the acclimation trials, three trials were recorded under the same instructions for determination of average preferred stride frequency (PSF) and preferred speed. Participants walked at seven different stride frequencies: $\Delta\omega$=PSF, ± 5, ± 10, and ± 15 strides/min. Stride frequency was prescribed by an auditory metronome with the instruction to coincide the right heel strike with the tone. Trials were repeated if an accurate and stable stride frequency was not achieved during the 3 m speed-up phase. The first set of seven stride frequencies were completed without any restrictions on walking speed (Free Speed condition, FS). Under a separate controlled speed (CS) condition, participants completed the same stride frequencies at approximately the same speed as the mean of the original preferred trials. Trials not completed within $\pm 10\%$ of the mean time to complete the preferred trials were repeated with a brief explanation to shorten or lengthen the stride. The CS condition was completed last to avoid any influence on FS trials. The stride frequencies were performed in a random order within each condition. Participants were provided with 30 s rest between trials.

2.4. Data analysis

Trials were of differing lengths. As λ^{max} and ApEn are sensitive to data length, trials were truncated to the middle 2000 data points for these analyses (separately, we performed the same analyses for a fixed number of strides, which produced the same pattern of results as presented here). Data was not filtered due to the influence of filtering on nonlinear measures (Stergiou et al., 2004a).

Peak knee flexion was detected for each stride of both legs, from which the mean and coefficient of variation (CV) were computed. Based on the time of each peak knee flexion ($t_{R(i)}$ and $t_{L(i)}$) the mean and CV of stride frequency were determined. The coordination between the knees was quantified by discrete relative phase in degrees:

$$\varnothing_{(i)} = 360 \times \frac{t_{R(i)} - t_{L(i)}}{t_{R(i+1)} - t_{R(i)}}, \quad (1)$$

from which the mean and SD were computed.

Local dynamic stability of the sagittal plane knee angular motion was determined as the maximum finite-time Lyapunov exponent (λ^{max}) following the Wolf algorithm (Wolf et al., 1985); computed using Chaos Data Analyzer software (J. C. Sprott, University of Wisconsin, 1995). For further description and illustration of the calculation of λ^{max} see Dingwell et al. (2001). Initial parameters for λ^{max} were determined for CDA; including Embedding Dimension (D), Accuracy (A), and Number (N). Embedding dimension was determined from the global false nearest neighbors algorithm (FNN), which uses time delay as an input parameter. Time delay was estimated from the first minimum of the average mutual information function and was computed independently for each file as input for FNN. Analysis indicated D of 6 was appropriate. Default values of (A) and (N) from CDA were chosen; set to 10^4 and 2, respectively.

The temporal structure of variability of the knee angle motion was assessed using Approximate Entropy (ApEn) (Pincus, 1991; Pincus and Goldberger, 1994). ApEn computes the logarithmic likelihood that runs of m length vectors which are close (within $r \times$ SD) remain close for vectors of length $m+1$. Parameter values of m=2 and r=0.2 were selected for this study. ApEn close to zero indicates consistent orderliness throughout the data, i.e. more predictable. For less predictable time series (i.e., more complex or noisy), ApEn is closer to a maximum value of 2. With the exception of λ^{max}, all measures were computed using Matlab code (Version R2009, Mathworks, Natick, MA) custom written by the authors or the Nebraska Biomechanics Core Facility, University of Nebraska—Omaha.

2.5. Statistical analysis

Hierarchical linear models (HLM) were employed as they provide model coefficients of the relationship between $\Delta\omega$ and dependent variables. HLM can be used on repeated measures design experiments, in contrast to linear regression which assumes independence of data. As well, different covariance matrix structures can be tested, avoiding the assumption of compound symmetry such as for repeated measures analysis of variance (Heck et al., 2010). The data file for participant 9 in the FS $\Delta\omega$=+15 condition was corrupted, but missing data is readily handled by HLM. We implemented HLM using the maximum likelihood method. Considering each speed condition separately, different models were examined using $\Delta\omega$ and/or $\Delta\omega^2$ as possible fixed effects, and subject intercept, $\Delta\omega$ and/or $\Delta\omega^2$ as random effects with different covariance matrix structures. The model with significant fixed effects and the lowest Akaike's information criterion corrected for finite sample sizes was selected as the most appropriate model. There is no widely accepted method for determining the proportion of variance accounted for by an HLM model, however we have provided an estimate using a