Relative Phase Coordination Analysis in the Assessment of Dynamic Gait Symmetry

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A variety of kinematic and kinetic measures are typically used to examine gait symmetry. Here we make the argument that gait asymmetries may be most clearly revealed through higher-order coordinative measures such as continuous relative phase (CRP). Participants walked on a treadmill with a load attached to their nondominant limb. Gait symmetry was then assessed using spatial (angular), temporal (velocity), and higher-order (CRP) symmetry measures. It was found that higher-order measures were most sensitive at assessing asymmetries due to load manipulation at both the distal and proximal segments. Symmetry measures derived from velocity variables were more sensitive than angular measures at detecting asymmetries, but were less sensitive compared with CRP. Asymmetries were also more readily detected using segmental angles compared with joint angles. These results suggest that gait asymmetries that emerge from changing constraints manifest along both spatial and temporal dimensions.

Keywords: locomotion, continuous relative phase, lower extremity, symmetry

Gait asymmetries have been assessed using a number of different variables, such as investigating the difference between the angular excursion or ground reaction force of the right and left limb (Munro et al., 1987; Herzog et al., 1989; Becker et al., 1995; Vagenas & Hoshizaki, 1989). Recent investigations have found that human gait is typically not perfectly symmetric; instead, healthy individuals exhibit some degree of asymmetry when walking (Haddad et al., 2006; Sadeghi et al., 2000). These asymmetries may not always be nonfunctional or detrimental to locomotion in that some degree of asymmetry may have functional consequences that allow the individual to adapt to changing task constraints. Studying how gait symmetry changes under varying task constraints may provide valuable information regarding mechanisms of gait adaptations in healthy individuals (Sadeghi et al., 2000).

Recent studies have used between-limb (Haddad et al. 2006) and within-limb (Barela et al., 2000; Haddad et al., 2006) continuous relative phase (CRP) analysis to assess gait asymmetries. Continuous relative phase symmetry measures have been adapted from the CRP techniques used to assess the spatiotemporal coordination patterns in human locomotion (e.g., Burgess-Limerick et al., 1993; Van Emmerik & Wagenaar, 1996; Hamill et al., 2000; DeLeo et al., 2004). The benefit of CRP analysis is that it takes into account both (angular) position and velocity in quantifying coordination and therefore captures the underlying spatiotemporal dynamics of intersegmental coordination. Research by Barela et al. (2000) and Haddad et al. (2006) hinted that CRP symmetry measures might lead to a more in-depth understanding of asymmetries in gait and may capture information regarding gait asymmetries that is not obtainable using measures that only use basic segmental kinematic data. The premise of this assertion is that CRP measures are more sensitive in capturing differences in within- and between-limb coordination patterns during walking. However, neither study directly compared CRP symmetry analysis with more traditional spatial measures such as joint or segmental angles.

In this study, participants walked on a treadmill while loads of varying weights were affixed to their nondominant ankle in order to vary the task constraints. Between-limb symmetry changes under different loads were assessed using relative phase (CRP), joint and segmental angular position, and angular velocity data. Based on work by Haddad et al. (2006) and Barela et al.
(2000), it was hypothesized that CRP symmetry measures would be more sensitive in detecting asymmetries during walking compared with the other symmetry measures of angular position and velocity.

**Methods**

**Experimental Setup and Protocol**

Six male and six female participants from the university undergraduate community (mean age = 20.58; mass = 71 kg; stature = 1.73 m) volunteered to take part in the study. All subjects were free of pathologies known to influence normal gait patterns. This experiment was approved by the University of Massachusetts Institutional Review Board; written informed consent was obtained before data collection began.

Three-dimensional kinematic data from the left and right lower extremity were collected at 60 Hz using six Qualisys cameras. Retro-reflective markers were bilaterally placed at the acromion process, greater trochanter, center of the knee joint, lateral malleolus, heel, and fifth metatarsal. Unilateral leg loads were secured to the non-dominant limb (defined as the limb the participant would use to kick a ball) 2.4 cm above the lateral malleolus using a custom-made leg-loading device (see Haddad et al., 2006, for a description of the leg-loading device).

Preferred walking speed was assessed by having the subjects tell the experimenter their preferred walking speed as the speed of the treadmill systematically increased. To minimize hysteresis effects, the same protocol was then repeated while the treadmill velocity decreased. The average of three increasing and three decreasing velocity trials were used to assess preferred walking speed. All experimental conditions were performed at the subjects’ preferred walking speed with loads of 0.0, 0.9, 1.8, 2.7, 3.6, and 4.5 kg secured to the loading device. The six conditions were randomized before data collection. In all conditions, subjects walked on the treadmill for 5 min at their preferred speed. Kinematic data were collected over the last minute. Therefore, participants were able to familiarize themselves with the treadmill at their preferred speed for 4 min before kinematic data were collected.

**Data Analysis**

The events of heel strike and toe-off were determined by examining the position of the foot throughout the trial (determined by the ankle, toe, and heel marker). When the heel first contacted the treadmill (before the belt of the treadmill carried the foot backward), a heel strike was scored. Toe-off was defined as the instant in time the toe lifted off the surface of the treadmill. The events of heel strike and toe-off were determined by custom-written Matlab algorithms and then visually confirmed by examining the position of the stick figure (created by the kinematic system) relative to the treadmill surface. In cases when the algorithm did not appear to properly identify the events, the experimenter would manually edit the heel strike and toe-off events. All kinematic data were filtered at 10 Hz using a recursive, low-pass, fourth-order Butterworth filter. Sagittal plane segment (absolute) angles were calculated relative to a right horizontal bilaterally for the thigh, leg, and foot. Sagittal plane joint (relative) angles were also calculated bilaterally for the hip, knee, and ankle. Segmental angular velocities were calculated using a central difference method. Continuous relative phase was calculated for three between-limb couplings (thigh-thigh, leg-leg, and foot-foot), and was calculated by first creating position-velocity phase planes normalized to a unit circle. Next, phase angles from each segment were calculated relative to the right horizontal of the phase plane. Finally, CRP was calculated by subtracting the phase angle of the loaded segment from the homologous unloaded segment. Continuous relative phase analysis was not performed on the joint angles. Previous research has shown that calculating CRP from joint angles is not appropriate due to the nature of joint angle time series (see Peters et al., 2003). All time series (joint angle, segment angle, segment angular velocity, CRP) were truncated on a stride-by-stride basis and interpolated to 100% of stride. Bilateral symmetry was then assessed for the segment and joint angular displacements and velocities, as well as the CRP time series. In all the time series, symmetry was calculated over the entire stride using an event-driven analysis. In this event-driven analysis, the left heel strike was time shifted such that the heel strikes of the left and right heel matched in time. Symmetry was then determined by subtracting the time series of homologous joints or segments across the entire stride (e.g., loaded thigh time series – unloaded thigh time series) and taking the absolute difference. In this analysis, perfect symmetry in all measures would be a continuous time series of zero degrees. In all symmetry measures, the loaded segment or joint was always subtracted from the unloaded segment or joint. However, since an absolute difference was used to calculate all symmetry couplings, it is irrelevant whether the loaded was subtracted from the unloaded or vice versa.

All statistical analyses were conducted over 10 strides by averaging the entire time series of each of the segmental and joint angles, angular velocities, and CRP couplings. A one-way within-subject repeated measures ANOVA was performed to determine significant differences between load conditions. Significance levels were set at \( p \leq .05 \). Tukey post hoc analysis was used to identify differences between leg loads.

**Results**

In the between-limb joint angular comparisons, slight deviations from symmetry were observed for all three joints (Figure 1). In the no load condition, the between-limb difference tended to remain around 5° over the entire time series. No effects of load were observed in the loaded hip–unloaded hip \( (p = .509) \), loaded knee–unloaded knee \( (p = .181) \), and loaded ankle–unloaded ankle \( (p = .185) \).
A small deviation (approximately 5°) from perfect symmetry was also observed in each of the segmental angle comparisons (Figure 2). In the segment angle symmetry, no effects of load were observed in the loaded thigh–unloaded thigh ($p = .384$) or loaded leg–unloaded leg ($p = .081$). However, significant effects of load were observed in the loaded foot–unloaded foot comparison ($p = .006$). Post hoc Tukey comparison of means revealed that in the foot segment angle symmetry measure, the no load condition was significantly different from the 3.6 and 4.5 kg conditions. Thus, unlike the joint symmetry measures, segmental symmetry measures revealed a significant effect of load distally.

In the segmental angular velocity comparisons, effects of load on symmetry were observed at the thigh ($p < .0001$), leg ($p < .0001$), and foot ($p < .0001$) (Figure 3). Post hoc Tukey comparison of means revealed that in the thigh velocity symmetry measure, the no load condition was significantly different from the 3.6 and 4.5 kg conditions, and the .90, 1.8, and 2.7 kg conditions were all significantly different from the 4.5 kg condition. In the leg velocity symmetry measure, the no load and .90 kg conditions were significantly different from the 2.7, 3.6, and 4.5 kg conditions; the 1.8 kg condition was significantly different from the 3.6 and 4.5 kg conditions; and the 2.7 condition was significantly different from the no load, .90, and 4.5 kg conditions.

The relative phase analysis also revealed a slight offset (approximately 5°) from symmetry in the baseline conditions (Figure 4). For the CRP data, significant effects of load on symmetry were observed at the thigh ($p < .0001$), leg ($p < .0001$), and foot ($p < .0001$). Thus, effects of load were observed distally and proximally. In each of the couplings, there was a significant increase from baseline as load was increased. Tukey post hoc analysis revealed that for each of the CRP couplings, all load levels were significantly different.
Discussion

In the current study, the CRP symmetry measure appeared to be more sensitive at detecting gait asymmetries compared with the other symmetry measures examined. All CRP segmental couplings showed systematic deviations from symmetry under all load conditions. This effect was observed not only for the segments closest to the attached load (foot and leg), but also more proximally at the thigh. The CRP analysis, therefore, was able to detect nonlocal adaptations and asymmetries to the imposed unilateral loads. In the joint angle symmetry measure, despite the imposed leg load, no symmetry changes were observed at the hip, knee, or ankle. In the segmental symmetry measures, changes in symmetry were only observed at the local segments close to the attached distal load (foot), with no proximal (thigh or leg) adaptations. Therefore, unlike the CRP symmetry measure, the segment angle symmetry measure was unable to detect changes in symmetry at the thigh. Interestingly, the segmental velocity symmetry measure did reveal changes at all segments, but were not as systematic as those observed in the CRP symmetry measure (compare Figures 3 and 4). Specifically, post hoc analyses revealed that the changes were generally between the heaviest and lightest loads. However, the CRP was able to detect changes at a greater resolution in healthy individuals while walking, where at each segment, all loads were significantly different from each other.

These findings have several important implications. Firstly, CRP symmetry measures are more sensitive at detecting imposed lower extremity asymmetries compared with symmetry measures that are derived only from angular position or angular velocity data. The CRP symmetry measure was able to detect asymmetries at all couplings examined, including the more proximal couplings even though the perturbation (leg load) was applied at the distal aspect of the leg. These proximal limb asymmetries may be important because they show that there is a systemic coordinative adaptation (rather than local adaptation) that is required when task constraints are altered. These asymmetries may be a functional
mechanism used by the nervous system to adapt to various constraints during locomotion.

Secondly, the segmental angle symmetry measure was able to detect imposed asymmetries at the distal (foot-foot) coupling. Interestingly, the joint angle symmetry measures were not able to detect the imposed asymmetry in any of the couplings (including the distal coupling). The reason why the segmental angular measures were more sensitive is unknown. However, it has been suggested that segmental angles are intricately related to the neurophysiology of central pattern generators (CPGs), and CPGs may control the segmental angles (Lacquaniti et al., 1999). In addition, the fact that segmental angle but not joint angle differences were observed suggests that the segments making up a joint vary in such a way that the resulting joint angle remains invariant.

Thirdly, most of the “added” information in the CRP measure (a variable that is derived from both angular position and velocity) may manifest from the angular velocity component rather than the angular position. Recall that, while both the angular velocity symmetry and position symmetry measures were less sensitive than the CRP symmetry measure, the angular velocity measures still revealed differences at all segments examined.

The final important finding of this study was that even in conditions where no asymmetry was imposed (no leg load added), the gait of healthy young adults was not perfectly symmetrical. Thus, some of the observed asymmetry in gait could be considered necessary or functional. In this study, all angular symmetry measures showed a baseline of about 5° of asymmetry. Although the exact magnitude of baseline asymmetry differed between subjects, the trend toward this asymmetry was shown in all subjects. These findings are consistent with previous research (for a review, see Sadeghi et al., 2000). It should, however, be noted that this baseline asymmetry could be the result of the error inherent in capturing and calculating angle and velocity data.

In conclusion, adaptations to imposed gait asymmetries are complex and appear to occur in both the proximal and distal limb segments. Continuous relative phase measures may be most sensitive in revealing these asymmetries. This may help clinicians and researchers in further establishing the conditions in which asymmetries may be functional or result in gait impairment or injury.

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References


