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Short communication

Computation of continuous relative phase and modulation of frequency of human movement

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ABSTRACT

Continuous relative phase measures have been used to quantify the coordination between different body segments in several activities. Our aim in this study was to investigate how the methods traditionally used to compute the continuous phase of human rhythmic movement are affected by modulations of frequency. We compared the continuous phase computed method with the traditional method derived from the position–velocity phase plane and with the Hilbert Transform. The methods were tested using sinusoidal signals with a modulation of frequency between or within cycles. Our results showed that the continuous phase computed with the first method results in oscillations in the phase time-series not expected for a sinusoidal signal and that the continuous phase is overestimated with the Hilbert Transform. We proposed a new method that produces a correct estimation of continuous phase by using half-cycle estimations of frequency to normalize the phase planes prior to calculating phase angles. The findings of the current study have important implications for computing continuous relative phase when investigating human movement coordination.

1. Introduction

Relative phase measures have been employed to capture the movement coordination that occurs between different body segments during many rhythmic motor activities (e.g., bimanual activities, postural coordination, locomotion and cycling). Although some researchers have used discrete measures of relative phase, in which the phase relationship is computed as the temporal difference between successive flexion or extension points of the movements (e.g., Diedrich and Warren, 1995; von Holst, 1973), continuous measures of relative phase are preferred (when possible) because they allow one to quantify the phase relationship across all the points of the cycle (Kelso, 1995).

Continuous relative phase $\varphi(t)$ is computed as

$$\phi(t) = \phi_1(t) - \phi_2(t) \tag{1}$$

where $\phi_1(t)$ and $\phi_2(t)$ are the continuous phase angles of the two oscillators. Traditionally, the continuous phase angle of an oscillator $\phi(t)$ is computed as

$$\phi(t) = \arctan\left(\frac{x'(t)}{x(t)}\right) \tag{2}$$

where $x'(t)$ is the velocity and $x(t)$ the position. Prior to calculating the phase angles, however, previous research has demonstrated the importance of normalizing the phase plane by dividing the velocity by $2\pi/p$, where p is the period of the oscillations (Peters et al., 2003). This normalization procedure allows one to obtain circular phase plane estimations irrespective of the frequency of the signal and to eliminate unexpected oscillations in the computed relative phase time-series.

To compute the continuous phase in experimental data composed of many cycles, researchers usually assume that the frequency of the signal is relatively constant (stationary) and therefore compute the average period or frequency of movement for the frequency normalization parameter. However, the frequency of human rhythmic movement is not completely stationary and constant variations of the frequencies have been demonstrated in movements that are self-paced and even constrained by a metronome (Torre and Balasubramaniam, 2009; Torre and Delignières, 2008). Knowledge that the frequency of human movement is often nonstationary has led researchers to return sometimes to discrete measures of relative phase to avoid

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problems. Because it has been demonstrated that continuous and discrete measures are not always equivalent (Peters et al., 2003), the Hilbert Transform has been often preferred as a secondary or alternate method for computing the continuous phase of a movement signal. The Hilbert Transform is based on the concept of the analytic signal introduced by Gabor (1946), whereby the

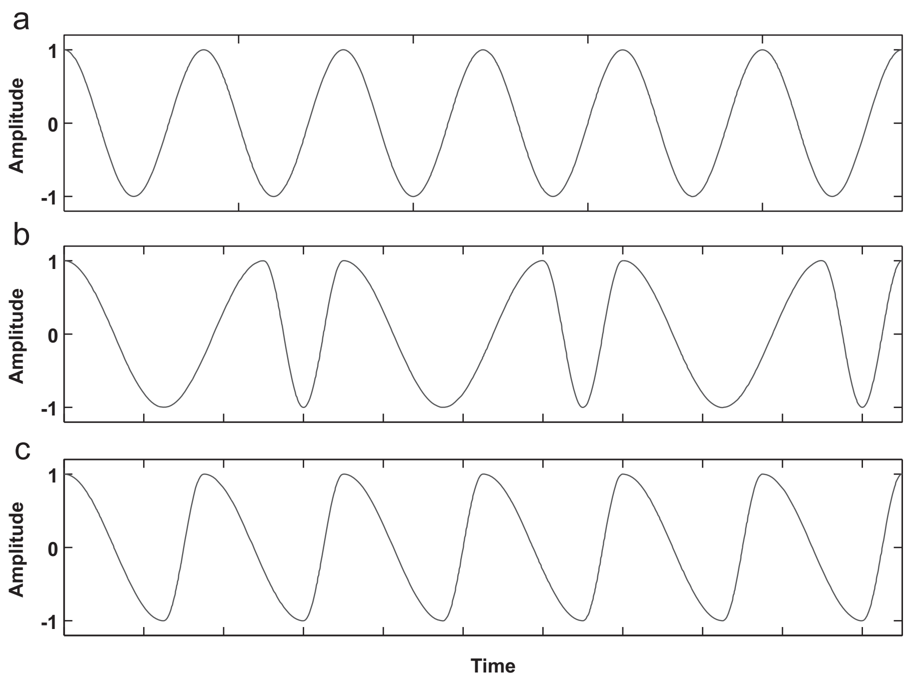

Fig. 1. Time-series of the three tested signals. (a) Sinusoidal signal without frequency modulations. (b) Sinusoidal signal with modulation of frequency between cycles. (c) Sinusoidal signal with modulation of frequency within cycles.

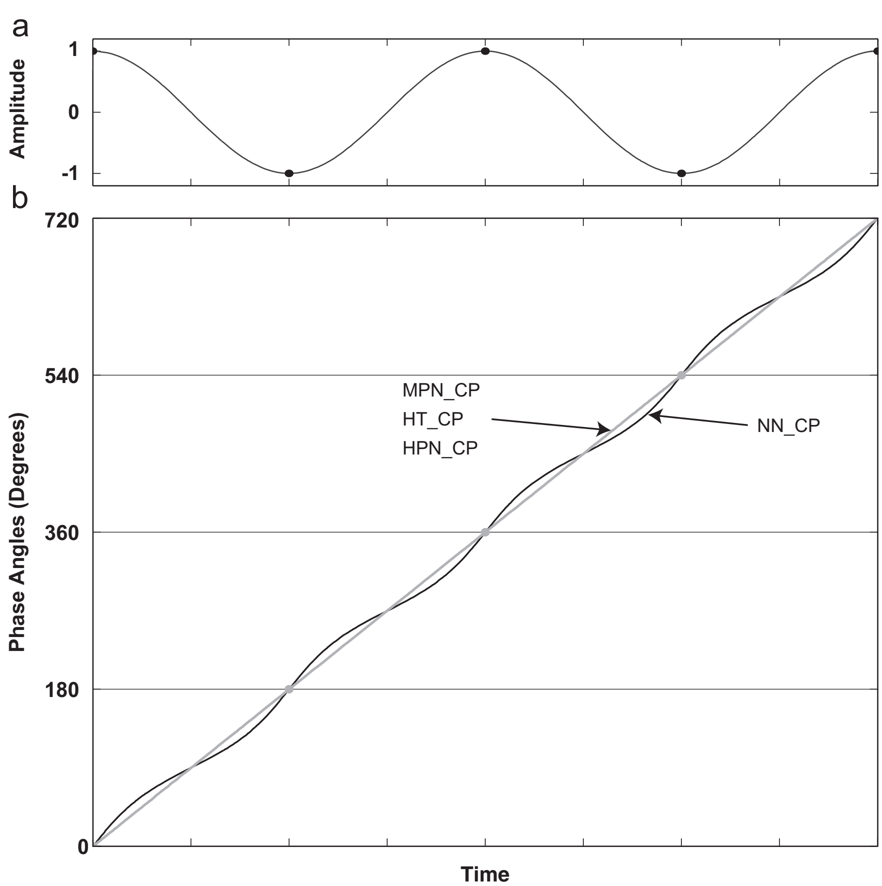

Fig. 2. (a) Sinusoidal signal without frequency modulations where the dots represent the inflexion points. (b) Phase angles computed with the four methods (NN_CP, MPN_CP, HT_CP and HPN_CP) where the dots represent the respective phase values at the inflexion points.

continuous phase angle is computed as

$$\phi(t) = \arctan\left(\frac{s(t)}{Hs(t)}\right) \tag{3}$$

where $s(t)$ and $Hs(t)$ are, respectively, the real and imaginary parts of the analytic signal (see Pikovsky et al., 2001 for more details).

The current study has two aims: (1) to show the limits of the mean frequency normalization and the Hilbert Transform to compute the continuous phase for signals that contain modulations of frequency, and (2) to demonstrate a method that uses the frequency of each half cycle of a rhythmic signal to normalize the phase plane to solve the issues highlighted in (1). We tested these methods with different sinusoidal signals that did or did not include modulations of frequency between and within cycles (Torre and Balasubramaniam, 2009).

2. Methods

The following four continuous phase methods were tested: (i) the Non Normalized Continuous Phase (NN_CP), which computes phase angles using Eq. (2) without normalization of velocity, (ii) the Mean Period Normalized Continuous Phase (MPN_CP) method, which computes phase angles using Eq. (2) with the velocity normalized by $2\pi/p$, where p is the average period of the signal, (iii) Hilbert Transform Continuous Phase (HT_CP), which computes phase angles using Eq. (3), and (iv) Half Period Normalized Continuous Phase (HPN_CP), which computes phase angles using Eq. (2) but with each half cycle of the velocity normalized by π/hp, where hp is the corresponding half period. Prior to normalizing the velocity, the last method requires first to determine each half-cycle period (hp), which is computed as the time difference between two inflexion points of the signal.

The four methods were tested on three sinusoidal signals: (1) without modulation of frequency, (2) with modulation of frequency between cycles and (3) with modulation of the frequency within cycles. All signals were composed of six cycles, with an amplitude of 1 and a sample rate of 1000 Hz. The first sinusoidal signal had a frequency of 0.25 Hz, the second corresponded to alternation of cycles at frequencies of 0.2 and 0.5 Hz and the third corresponded to alternation of half cycles at frequencies of 0.2 and 0.5 Hz.

3. Results

The three signals tested in this study are represented in Fig. 1. The continuous phase angles computed with the four methods for the different sinusoidal signals are presented in Figs. 2, 3 and 4. We discarded the two first and last cycles of each time-series because the continuous phase computed with the Hilbert Transform presents distortions at the beginning and at the end of the computed phase time-series that need to be removed (Pikovsky et al., 2001).

As expected, the MPN_CP, HT_CP and HPN_CP methods provided a similar and correct estimation of the continuous phase for the first signal (without modulation of frequency). The continuous phase increased linearly and phase angle values of 0°, 180°, 360°, 540° and 720° corresponded correctly to the inflexion points (see Fig. 2). In line with previous research, however, the continuous phase computed without normalization (NN_CP) contained oscillations that are not expected for a sinusoidal signal (Peters et al., 2003). Consequently this method is not recommended under any condition.

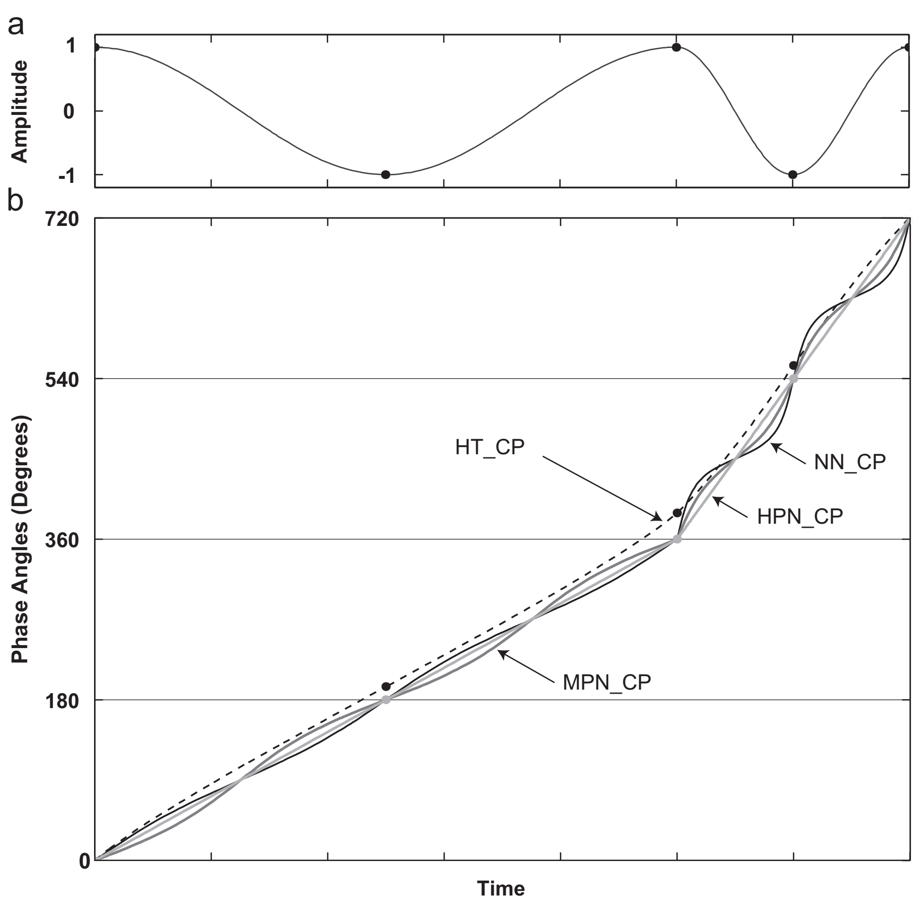

Fig. 3. (a) Sinusoidal signal with modulation of frequency between cycles where the dots represent the inflexion points. (b) Phase angles computed with the four methods (NN_CP, MPN_CP, HT_CP and HPN_CP) where the dots represent the respective phase values at the inflexion points.

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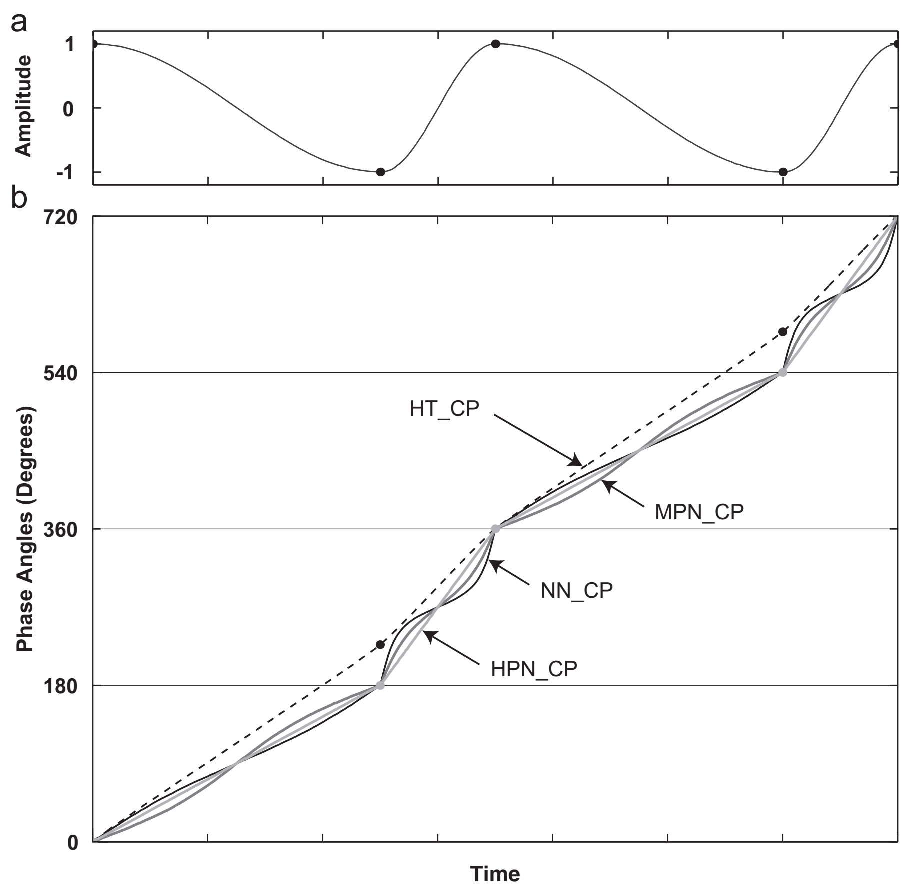

Fig. 4. (a) Sinusoidal signal with modulation of frequency within cycles where the dots represent the inflexion points. (b) Phase angles computed with the four methods (NN, CP, MPN_CP, HT_CP and HPN_CP) where the dots represent the respective phase values at the inflexion points.

For the second signal (modulation of frequency between cycles) although the continuous phase computed with the four methods increased faster for the second cycle because of the difference of frequency, the manner in which the continuous phase increased across the cycles was different for the four methods (see Fig. 3).

The NN_CP and MPN_CP methods provided a correct estimation of the phase angles at inflexion points, but the continuous phase did not increase linearly and contained oscillations that are not expected for a sinusoidal signal. The continuous phase increased linearly for the HT_CP method, but there was an overestimation of the phase angle that was clearly observable at the inflexion points. With a linear increase of the continuous phase and a correct estimation of the phase values at the inflexion points, the HPN_CP method was the only method that gave an exact estimation of the continuous phase.

For the third signal (modulation of frequency within cycles) the continuous phases computed with the four methods increased faster for the second half cycle because of the difference of frequency. As for signal two above, however, there were differences between the continuous phases computed with the four methods (see Fig. 4).

A correct estimation of the phase angle values was obtained at inflexion points for NN_CP and MPN_CP methods, but the continuous phase did not increase linearly. The HT_CP method also overestimated the phase angles except at the maximal inflexion points. Again, the HPN_CP method provided the only accurate estimation of the continuous phase with a linear increase and a correct estimation of the phase values at the inflexion points.

4. Discussion

By showing incorrect estimations of continuous phase angles when the frequency of the signal was not constant, the current study demonstrates the limitations of the phase computation methods traditionally used. Our results revealed that the continuous phase computed with the velocity normalized by $2\pi/p$, where p is the average period of the oscillations (MPN_CP), results in oscillations not expected for a sinusoidal signal and that the continuous phase is overestimated with the Hilbert Transform (HT_CP). Such results encouraged further explorations of Hilbert Transform limitations and the results (not reported here) have showed that the estimation of the continuous amplitude with the Hilbert Transform often used by researchers is also affected when signals present modulations of frequency.

For the signals tested here, correct estimations of the continuous phase were only obtained using the HPN_CP method, in which the velocity was normalized for each half cycle by π/hp, where hp is the corresponding half period. Normalization of the velocity for each cycle by $2\pi/p$, where p is the corresponding period, would be sufficient for signals with a modulation of frequency between cycles. However, normalization of the velocity by half cycle is more appropriate for human movement data because between and within cycles, modulations are often present at the same time (Torre and Balasubramaniam, 2009).

In conclusion, the current study extends previous research that has shown how subtle nonstationarities in human rhythmic movement can affect continuous phase computation (Fuchs et al., 1996; Kurz and Stergiou, 2002; Peters et al., 2003).

The results reveal that the methods traditionally used to compute the continuous phase of rhythmic movements are limited when these signals have modulations of frequency and that this problem can be solved by normalizing the phase plane for each half-cycle. Accordingly, the half-cycle normalization method proposed here (i.e., HPN_CP) should be employed to best index the pattering and stability of rhythmic human movement and coordination.

Conflict of interest statement

None declared.

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