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Research article

Using Mean Absolute Relative Phase, Deviation Phase and Point-Estimation Relative Phase to Measure Postural Coordination in a Serial Reaching Task

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Abstract
The objectives of this communication are to present the methods used to calculate mean absolute relative phase (MARP), deviation phase (DP) and point estimate relative phase (PRP) and compare their utility in measuring postural coordination during the performance of a serial reaching task. MARP and DP are derived from continuous relative phase time series representing the relationship between two body segments or joints during movements. MARP is a single measure used to quantify the coordination pattern and DP measures the stability of the coordination pattern. PRP also quantifies coordination patterns by measuring the relationship between the timing of maximal or minimal angular displacements of two segments within cycles of movement. Seven young adults practiced a bilateral serial reaching task 300 times over 3 days. Relative phase measures were used to evaluate inter-joint relationships for shoulder-hip (proximal) and hip-ankle (distal) postural coordination at early and late learning. MARP, PRP and DP distinguished between proximal and distal postural coordination. There was no effect of practice on any of the relative phase measures for the group, but individual differences were seen over practice. Combined, MARP and DP estimated stability of in-phase and anti-phase postural coordination patterns, however additional qualitative movement analyses may be needed to interpret findings in a serial task. We discuss the strengths and limitations of using MARP and DP and compare MARP and DP to PRP measures in assessing coordination patterns in the context of various types of skillful tasks.

Key words: Postural coordination, mean absolute relative phase, deviation phase, point-estimation relative phase.

Introduction

This paper examines the use of relative phase measures to characterize postural coordination strategies, which may add to the understanding of how the postural system is regulated during functional movements. However, relative phase measures have broader application in describing coordination patterns under various skillful tasks, and demonstrating coordination changes during of learning of motor skills and after injuries. Relative phase measures the relationship between two joint or body segment angles to characterize inter-joint coordination patterns. Since relative phase measures incorporates both spatial and temporal aspects of angular movement, it may be more sensitive to picking up differences of coordination patterns (Haddad et al, 2010; Kurz and Stergiou, 2004). Relative phase measures have been used to measure limb coordination during walking (Barela et al., 2000; Burgess-Limerick et al., 1993; Kurz and Stergiou, 2002; 2004, Haddad et al, 2010), weightlifting (Hu and Ning, 2015), swimming (Komar, et al., 2014), swinging (Teulier and Delignières, 2007) and gymnastic skills (Gautieret al, 2009). Stable and unstable coordination patterns have been found using relative phase with oscillating bimanual tasks (e.g. Kelso, 1984; Milliex et al., 2005), visual tracking postural tasks and matching postural coordination to ankle-hip position plane figures (e.g. Bardy et al., 2002; Faugloire et al., 2006; 2009, James, 2014). Relative phase between pelvis and trunk movements are used to identify coordination changes in individuals with low back fatigue during weightlifting (Hu and Ning, 2015) and for those persons with low back pain during sit to stand tasks (Shum et al 2005). Runners with low back pain showed differences in trunk and pelvis continuous relative phase during walking and running when compared to runners without a history of low back pain (Seay et al, 2011). Relative phase measures have also been applied to examine coordination during learning of sports related tasks, such as swimming (Komar et al, 2014), swinging (Teulier and Delignières, 2007) and gymnastic skills (Delignières, et al, 1998; Gautieret al, 2009). All of the tasks studied can be characterized to have either discrete or continuous movements.

Mean absolute relative phase (MARP), deviation phase (DP) and point-estimation relative phase (PRP) are potential measures to characterize coordination during the performance of tasks. We focus on postural coordination during the performance of a serial reaching task. MARP and DP are single measures derived from continuous relative phase curves that could quantify coordination patterns and describe the stability of the patterns during functional movements. PRP measures relative phase by comparing the time to maximal or minimal angular displacement of one joint within a cycle of angular displacement of a reference joint (Kurz and Stergiou, 2004; Wheat and Glazer, 2006; Zanone and Kelso, 1992). Basic descriptive statistics of PRP across the movement cycles provides information about coordination modes and variability within a single trial (Bardy, 2005; Bardy et al., 2002; Fauglorie et al., 2006, Oullier, et al, 2002). Postural coordination patterns have previously been characterized in terms of in-phase (close to 0 degrees) and anti-phase (close to 180 degrees) hip and ankle relationships in visual tracking tasks using PRP (Bardy et al., 1999; Bardy, et al., 2002; Faugloire, et al., 2006; Oullier et al., 2002; James, 2014). In-phase and anti-phase postural coordination patterns may also be demonstrated during reaching tasks.

The selection of a relative phase measure must re-

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late to the type of movement within the task being assessed, e. g. continuous or discrete movements. PRP measures may be easily attained during continuous cyclical movement tasks, such as walking or frequency induced postural sway, where clear displacement peaks of the comparison angles are repeatedly attainable. MARP has been proposed as a valid measure of joint relationships during gait cycles (Kutz and Stergiou, 2004) and might also characterize in-phase and anti-phase postural sway patterns. Because MARP is an average of a continuous relative phase curve over the duration of a movement, lower values are interpreted as representing more in-phase associations while higher values are interpreted as indicating more anti-phase relationships. Low DP values are considered to represent increased stability whereas high DP values represent decreased stability of the coordination pattern (Kurz and Stergiou, 2004). MARP and DP may be of greater value during the analysis of discrete movements or phases of movements where a description of the dynamics of the inter-joint interactions across the entire movement is desired.

We have used MARP for examining proximal and distal postural coordination strategies during discrete reaching (Galgon and Shewokis, 2006). In a pilot study, five healthy young adults performed a discrete arm raising and lowering reaching task with arm conditions (unilateral versus bilateral arm movements) and different target heights (three targets separated by 17 cm, vertically). Changes in postural coordination dynamics as measured by MARP were evident when examining different task constraints. Target height had a main effect on dominant shoulder-ipsilateral hip MARP, $F_{2,8} = 38.75$, $p < .0125$. Arm condition had a main effect on dominant shoulder-contralateral hip MARP and contralateral hip-ankle MARP, $F_{1,8} = 59.62$ and $F_{1,8} = 41.81$, $p < .0125$, respectively (Galgon and Shewokis, 2006). The results supported anticipatory postural adjustment changes associated with reaching arm conditions (Zattara and Bousissett, 1988) and target variations (Kiminski and Simpkins, 2001). The quantitative (MARP) results also supported the qualitative analysis (angle-angle plots) using techniques described by Winstein and Garfinkel (1989) for arm variation on postural coordination.

In our investigation of postural coordination during the learning of a novel serial reaching task, we were concerned as to whether these measures would provide a description of postural coordination that could be consistently quantified across practice. The serial reaching task included 15 sequential up and down arm movements that the subjects learned across three days of practice by following light targets, which were displayed in front of them (Figure 1). In this work we have shown that participants improved their hand accuracy and consistency in matching their hand heights to the vertical targets across practice. Participants also improved their postural regulation as measured by time to boundary derived from center of pressure data (Galgon et al., 2010). We are interested in determining, if postural coordination strategies also change when learning this dynamic serial task. Selecting a relative phase measure seems appropriate; however there remains a limitation in that the movements generated during this task could not easily be classified as either continuous or discrete.

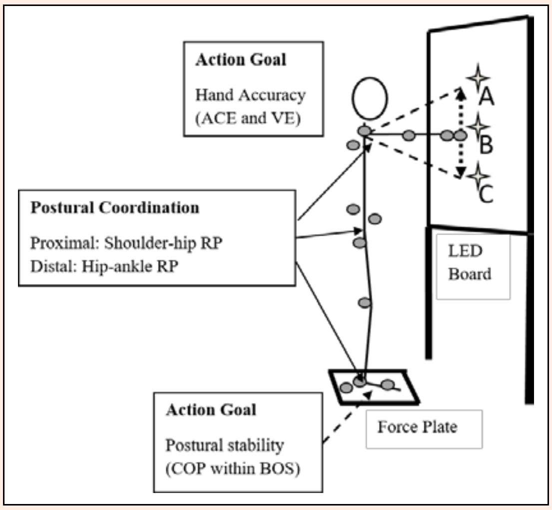

Figure 1. A representation of the set up for serial reaching task. Participant stood facing an LED board with arms extended out in front to match hand height to one of three vertical targets. Kinematic representation of arm, trunk and leg segments were attained from markers attached to boney landmarks. Angular displacement and velocity at shoulder, hip and ankle were used to calculate relative phase (RP) to characterize postural coordination within two action goals, hand accuracy and postural stability.

A problem in calculating PRP within a multistep task is selecting reference points; the peaks and/or troughs in the angular displacement time series that are used for the maximum or minimum values (Wheat and Glazer, 2006). Changes in angular displacement of postural joints may be small and gradual, which may additionally contribute to problems when selecting the reference points for analyzing postural coordination. Using MARP and DP may be a problem in a serial task because discontinuous movements may create phase distortion in continuous relative phase curves. Phase distortions may include phase shifts (Kurz and Stergiou, 2002) or phase wrapping (Milliex et al., 2005), typically associated with 360-degree phase angle data. A phase shift is a temporary 360 degree shift in the relative phase data array (Kurz and Stergiou, 2002). The shift occurs when the instantaneous phase angle of one joint crosses over the zero axis (values change from 360 to 0 degrees) with the comparison joint phase angle crossing the axis at a later time. The result is a temporary $\pm$ 360 degree jump in the continuous relative phase curve. Phase wrapping occurs when there is no consistent relationship between the comparison angles or when the relative phase is non-stationary (Milliex et al., 2005), e. g. when one joint was moving and the other was relatively stationary. Phase distortions induce inflation in MARP and DP values, if the distortions are not corrected. PRP measurements may be more easily applied to a serial task because the relative phase is not averaged over a complete cycle and the asymmetries and irregularities in the actual motion are eliminated (Zanone and Kelso, 1992) and phase distortions do not need to be accounted for in the calculations. However, PRP measures could potentially miss important interjoint relationship changes during a serial task. These PRP omissions might occur between point-estimations.

Although these relative phase measures are not novel in describing movement coordination patterns, they have primarily been applied to measuring postural coordination in oscillating tasks and have not been reported in the analysis of coordination for standing and reaching tasks. To our knowledge, using relative phase measures to assess the coordination dynamics of serial tasks has not been done. Within the method section, we describe visual inspection of the data and define the corrections made to the relative phase curves to ensure consistent calculation of MARP, DP and PRP with the serial reaching task. We present a comparison of the MARP and DP measurements to the PRP measurements in a subset of subjects who participated in a study examining the learning of a novel serial reaching task. Our purpose is to present the methods we used to calculate postural coordination dynamics and discuss the strengths and limitations of each measure within the context of a serial reaching task.

Methods

Participants

Seven participants were randomly selected from a sample of healthy young adults who had originally consented to participate in a learning study (Galgon et al., 2010). These seven individuals included 2 males and 5 females (mean age of 25 ± 3 years; mean shoulder height of 1.42 ± 0.08 m; mean weight of 74.4 ±12.7 kg). Participants were included if they were between 18-49 years, and excluded, if they felt they could not easily perform the required activities, could not participate in all experimental sessions, or had any disorder that may affect their performance, such as an acute or chronic musculoskeletal condition, a vestibular or some other neurological disorder. Prior to recruitment, institutional internal review board approval was obtained.

Instrumentation and initial processing

A light emitting diode (LED) board (David Solomon, Department of Neurology, Johns Hopkins), a large plywood board mounted to a rolling frame with embedded LEDs, was used as targets to direct arm movements. Customized timing programs (Labview 5.02 software, National Instruments) operated the LED board. To detect each target LED onset, a five volt signal was input into a Peak System's 12 bit A-to-D interface unit (Peak Performance Technologies, Centennial, CO.). The LED board was positioned one arm length plus 10 inches in front of the participants. The LED targets were set such that during an anterior reach with the elbows extended toward the middle target (B), the shoulders were positioned at approximately 90 degrees of flexion. Two additional LED targets were 17 centimeters vertically above (A) and below (C) the middle LED target.

Three-dimensional kinematic data was obtained from a four (60 Hz) video camera system (Peak Performance Technologies, Centennial, CO). Reflective markers were attached to bony landmarks (lateral acromium, lateral epicondyle, lateral styloid process, C8 and S1 spinous processes, anterior iliac spine, greater trochanter, lateral tibial plateau, lateral malleolus, calcaneous, and between the second and third metatarsals on dorsum of the foot) to create body segment representations of the trunk, upper and lower extremities. Peak Motus, version 8.2, was used to: (a) digitize marker images, (b) capture the raw kinematic data and (c) calculate sagittal plane angular displacements for the right shoulder, hip, and ankle. Angular velocities were calculated using the central difference method. Angular displacement and velocity data was smoothed with a 4th order 6 Hz Butterworth low pass filter. The kinematic data was also matched to the target signal onsets. Figure 1 presents the experimental set up including a schematic of markers to represent the body segments.

Experimental procedure

Each participant stood with their arms fully extended, with forearms pronated, hands resting on the thighs and grasping a wooden rod facing the LED board. A tone sounded to inform the participant to get ready and was followed by the lighting of target B. The participant moved their hands to the level of target B. A 15 step sequence of lights, using targets A, B and C, was presented at 1-second intervals. The sequence ended on target B and a tone signaled the end of the trial. The sequence was practiced for 100 trials, with rests of approximately 30 seconds between trials and 1-3 minutes between blocks of ten trials. Prior to each block, the following instructions were given: "match the rod to the level of each target as fast as possible after the light turns on." The participants did not receive feedback on their performance. The participants performed 100 trials for two additional sessions with a 12-36 hour interval allowed between practice sessions (Galgon et al., 2010).

MARP and DP calculations

A representation of the steps to calculate the continuous relative phase curve for shoulder-hip coordination for an upward and downward arm movement is illustrated in Figure 2. The angular displacements (θ) and velocities (ω) were normalized using the following equations:

1) normalized $\theta_i = [2x(\theta_i - \min(\theta_i))/ \max(\theta_i) - \min(\theta_i)]-1$, and
2) normalized $\omega_i = \omega_i/\max(|\omega_i|)$,

where i represents each iteration in the data array, $\min(\theta_i)$ and $\max(\theta_i)$ equals the minimal and maximal points in angular displacement data array, and $\max(|\omega_i|)$ equals the maximal value in the absolute angular velocity data array. Normalized angular displacement and velocity time series were used to construct phase plane portraits for shoulder, hip and ankle joints, separately (Barela et al., 2000; Kurz and Stergiou, 2002). Normalization placed the phase plane portraits in a polar coordinate system with a center origin (Wheat and Glazier, 2006) and was required to accommodate the joint differences in ranges of angular displacements. For example, within a trial, shoulder angle displacement might range from 60 to 100 degrees of shoulder flexion and hip angle displacement

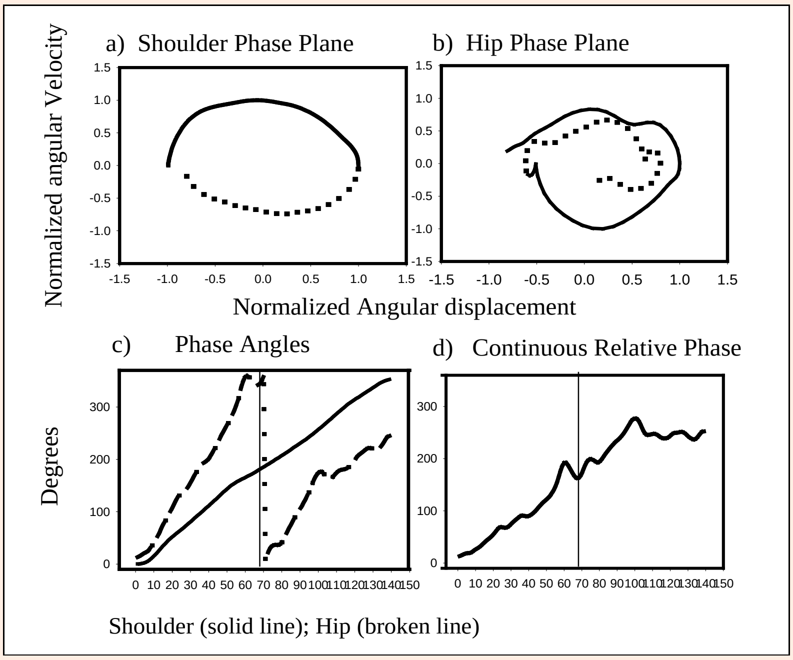

Figure 2. The method for calculating relative phase: a) shoulder and b) hip phase plane portraits during upward (solid line) and downward (dotted lines) movements; c) shoulder and hip phase angles and d) relative phase between the two joints (vertical line separate upward and downward movements).

might range from -15 to -5 degrees of hip flexion. Without normalization the phase plane portraits would be plotted in different quadrants (positive x quadrants for the shoulder and negative x quadrants for hip), resulting in altered phase angle calculations and incorrect relative phase values. Phase angle (φ) time series were calculated as φ_i = arctan [normalized (ω_i) / normalized (θ_i)] from each phase plane portrait. Two continuous relative phase curves were constructed to represent proximal (shoulder–hip) and distal (hip-ankle) postural coordination dynamics, separately. Relative phase curves were calculated as equal to the i^{th} point in the phase angle curve of the distal joint minus the i^{th} point in the phase angle curve of the proximal joint (Barela et al., 2000; Kurz and Stergiou, 2002). MARP was calculated, as $\Sigma^{N}_{i=1}$ |Relative Phase|/N, during each trial. DP was calculated as the average of the standard deviation of the i^{th} point on the absolute relative phase curves for 10 trials in a measurement epoch, $\Sigma^{N}_{i=1}$ |SD|/N. MARP and DP were calculated for each movement interval and then averaged across all intervals to obtain the final values.

Prior to MARP and DP calculations, visual inspection of continuous relative phase curves and corrections to phase shift distortions were made. To keep corrections as consistent as possible and to prevent changing the dynamics of the curve for the MARP and DP calculations, four rules were used:

1) If the relative phase curve was close to 180 degrees (90° > *i* < -90°), phase shifts were corrected in the positive direction (+360°). Figure 3a demonstrates a corrected curve when the data array was closer to 180 degrees.

2) If the relative phase curve was close to zero (90°< *i* > -90°), phase shifts were adjusted by ± 360° to maintain array trajectory close to zero. Figure 3b demonstrates phase shift corrections for a data array that was close to zero.

3) When a ±360° shift in the relative phase curve occurred during phase wrapping, no correction to the data was made, because the shift was not temporary and a bias in the MARP toward mid-range values was assumed. Figure 3c demonstrates an uncorrected relative phase curve where phase wrapping and a shift in occurred.

4) Relative phase values between ±270° and 360° were adjusted to ±90° to 0° to account for redundancy of the 360 degree data. We assumed that values between ±270 to 360° were closer to an in-phase coordination pattern. This correction prevents a skew toward a higher MARP value, which may result in a misinterpreted anti-phase coordination relationship.

Since all corrections either added or subtracted 360 degrees to the original relative phase curve, there was no change in the curve dynamics with respect to the direction or slope of the curve.

PRP Calculation

Angular displacement time series for the shoulder, hip, and ankle were used to calculate PRP. PRP was calculated using the following equation: $[(t_{target} - t_o)/(t_{reference} - t_o)] \times 360°$, where t_o = time of the origin maximum point of a reference angle or the start of cycle, t_{target} = time of maximum point of comparison angle within the cycle, and $t_{reference}$ = time of maximum point of reference angle at the end of cycle (Zanone and Kelso, 1992). The hip angular displacement time series gave the most consistent repeated peaks across the trials. Therefore, the hip was

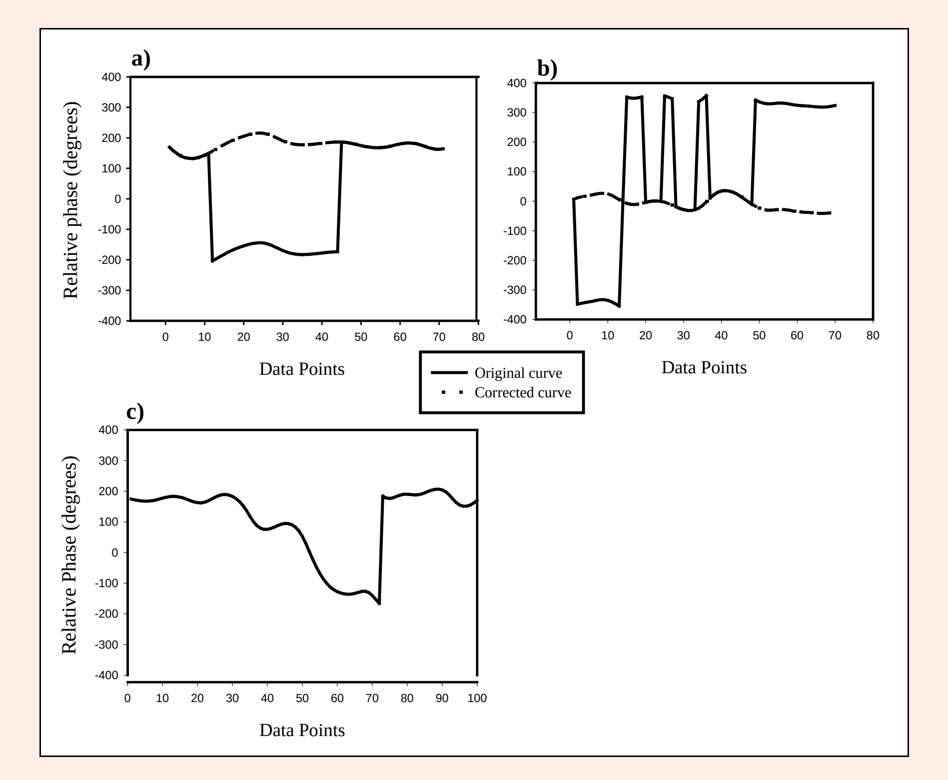

Figure 3. Corrections to the continuous relative phase curves for phase shifts: a) where data trajectory is close to 180 º, b) when data trajectory is close to 0 º, and c) during a phase wrapping when no correction was made.

designated as the reference angle and the shoulder and ankle were designated as target angles for the proximal (shoulder-hip) and distal (hip-ankle) PRP measurements (Figure 4 a-b). Peaks in angular displacement were identified as the maximum value in the time series within each of the 15 arm movement intervals. In order to identify consistent periods, two intervals were considered to represent a cycle (one up and down arm movement). As a result, the peaks of the reference angle were determined from the maximum values in intervals 1 and 2 for period one, 3 and 4 for period two, and so forth. The average of the estimated points from five to seven periods determined the PRP for each trial. Visual inspection of the time series was required to determine if maximum points were identified correctly. Periods were removed from the average, if either the reference or target angles did not have an observable peak during that period (Oullier et al., 2002).

Data analysis

This study used a repeated measures design to examine the participants' performances across three practice sessions. The proximal and distal MARP, DP, PRP measures were determined by the average value of 10 trials at three points, early (trials 6-15) middle (trials 46-55) and late (trials 86-95) during practice within each of three sessions (S1, S2, and S3). Standard deviations (SD) across the ten trials and the average inter-trial SD for MARP and PRP were calculate to look at the variability of each measure. Paired t- tests (two-tailed) were calculated to determine if MARP, DP, PRP and inter-trial SD of PRP would distinguish between proximal and distal joint dynamics and during early (S1 early) and late practice (S3 late). Cohen's *d* effect size index was used. Correlations and the 95% confidence intervals (CI) of the correlations were calculated between each of the measures from all 9 measurement points.

Results

Table 1 displays means and SD of the seven participants for all the measures during early and late practice of the serial reaching task. Mean proximal PRP and MARP values were similar, but mean distal PRP values appear closer to 180 degrees than distal MARP values. Although practice did not have a group effect on MARP, PRP and DP values, individual differences were found with some participants' relative phase values changing in different directions. Figure 5 illustrates the different directional changes in continuous relative phase curves, MARP, PRP and DP values from early to late practice by two participants.

Both MARP and PRP values could distinguish between proximal and distal joint dynamics (t_{62} = 5.79, p < 0.001, d = 0.74 and t_{62} = 10.54, p < 0.001, d = 1.34, respectively). DP values distinguish between the variability in proximal and distal joint relationships (t_{62} = 6.34, p < 0.001, d = 0.81), but inter-trial SD of PRP did not. Distal MARP, PRP, and DP values were significantly higher than proximal values.

Shoulder- hip MARP and PRP were strongly related (r = 0.86, *95% CI* = [0.78, 0.91]). Figure 6a presents the linear relationship between proximal MARP and PRP values. Because of a natural break in the relative phase

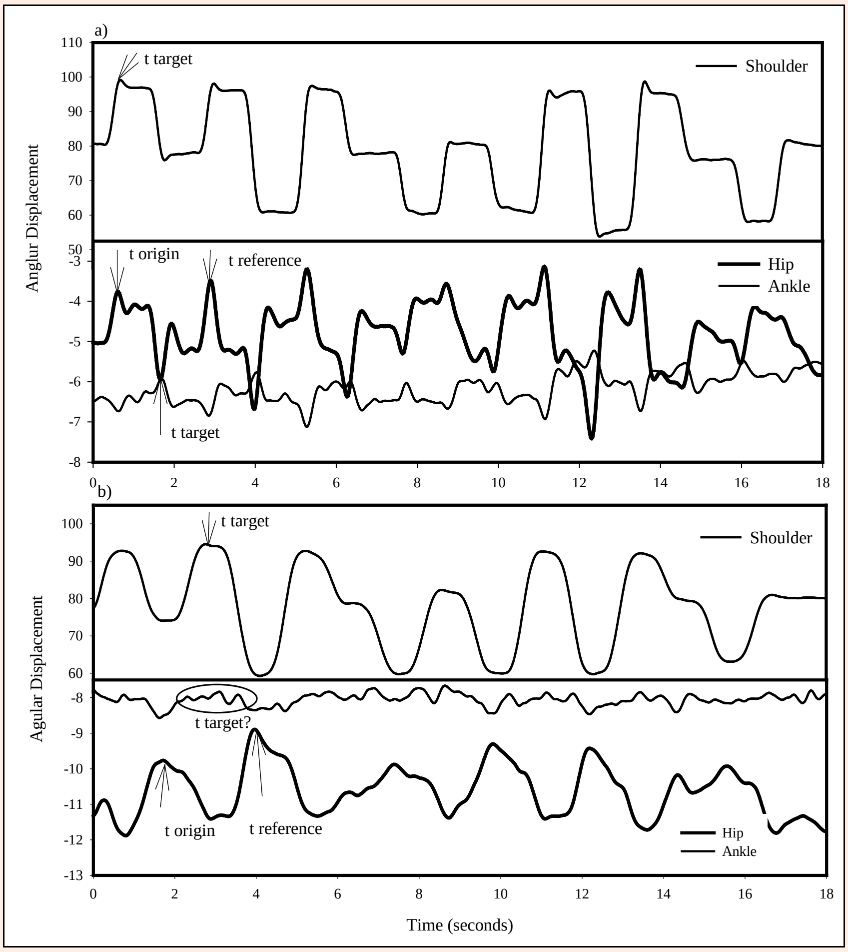

Figure 4. Graphs of shoulder, hip and ankle angular displacement; a) in a participant using a serial arm movement pattern and b) a participant using a continuous arm movement pattern. Maximal points identify time (t) for origin and reference and target points used to calculate point-estimation relative phase.

Table 1. Means and standard deviations (SD) of Mean absolute relative phase (MARP), Point-estimation relative phase (PRP), Deviation phase (DP), and across trial SD and inter-trial SD of MARP and PRP; for seven participants who practiced 300 trials of serial reaching tasks. Measurement points represent Early session 1 (S1) and late session 3 (S3). All values are in degrees.

	Shoulder- Hip		Hip-Ankle	
	Early S1	Late S3	Early S1	Late S3
MARP	115.72 (27.20)	114.52 (40.33)	132.86 (16.53)	143.66 (9.66)
PRP	116.59 (27.88)	114.49 (42.96)	166.01 (7.16)	167.23 (13.67)
DP	50.37 (6.48)	51.10 (10.89)	60.17 (7.41)	62.31 (6.53)
Across trial SD of MARP	14.06 (5.81)	14.27 (6.79)	19.09 (5.76)	18.08 (4.76)
Across trial SD of PRP	13.67 (6.68)	16.38 (4.67)	22.05 (7.90)	23.68 (5.29)
Inter-trial SD of MARP	35.92 (4.87)	43.51 (7.65)	35.50 (8.45)	39.92 (5.65)
Inter-trial SD of PRP	49.70 (19.96)	61.53 (13.97)	53.16 (13.49)	63.59 (9.06)

DP measures the variability across 10 continuous relative phase curves in each measure point. Across trial SD of MARP and SD of PRP measures the variability of the values across 10 trials within each measurement point. Inter-trial SD of MARP and PRP measures the variability of the values within each trial.

data, proximal MARP and PRP data were categorized as greater or less than 100 degrees. Two individuals had shoulder-hip MARP and PRP values less than 100 degrees and five individuals had values that were consistently above 100 degrees. When values were categorized above and below 100 degrees, a strong association was found between MARP values and variability, DP (r = -0.70, *95% CI* = -0.81, -0.55 and r = 0.70, *95% CI* = 0.55, 0.81) for values > and < 100°, see Figures 6 b-c). Only PRP values less than 100 degrees were moderately associated with variability, inter-trial SD of PRP (r = 0.55, 95% *CI* = 0.33, 0.70). Hip-ankle MARP and PRP exhibited low associations (r = -0.21, *95% CI* = -0.39, 0.04), while all hip-ankle MARP and PRP values were greater than 100 degrees. Hip-ankle MARP was inversely related to inter-trial SD of Hip-ankle MARP (r = -0.74, *95% CI* = 0.60, 0.83) and Hip-ankle DP (r = -0.80, *95% CI* = - 0.87, -0.69). The MARP and DP associations suggest that when MARP values are closer to 0° or 180° there are lower DP values or less variability, and when MARP values were at

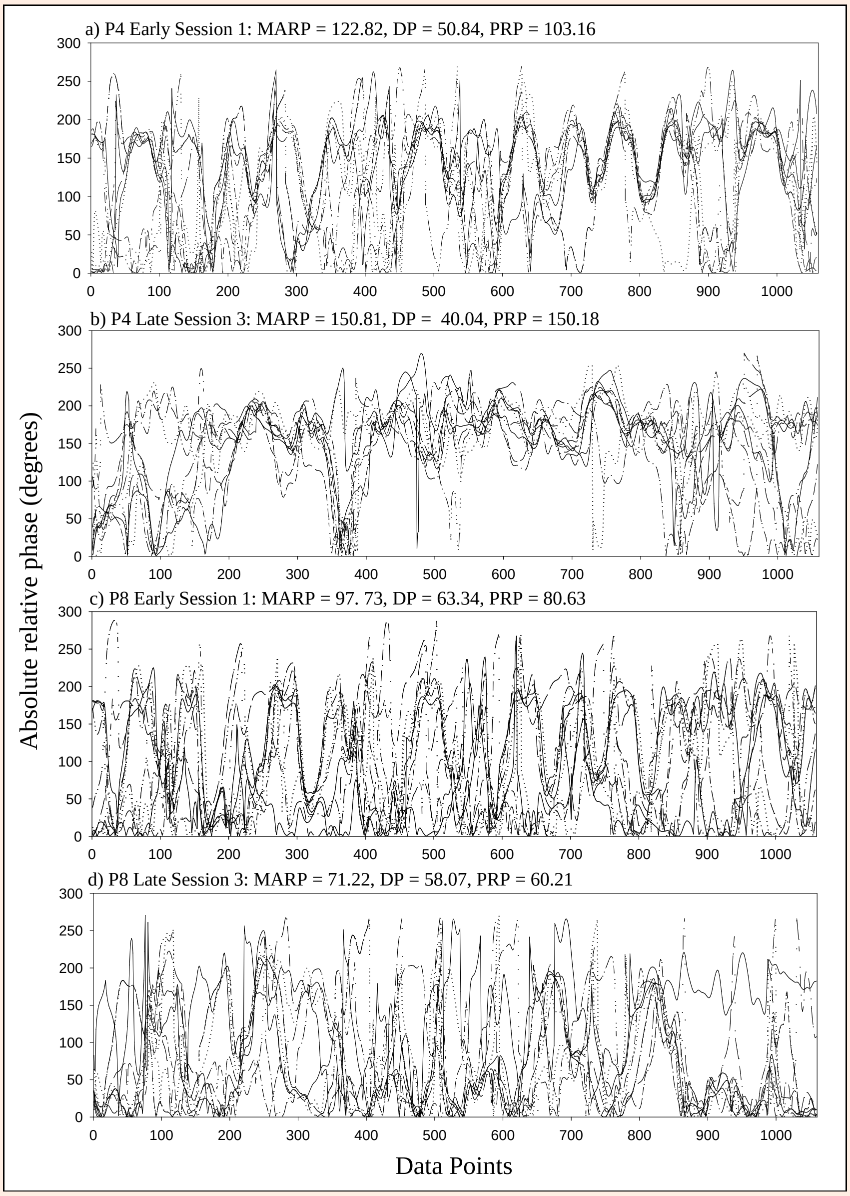

Figure 5. Each graph represents ten shoulder-hip (SH) continuous relative phase curves for participants 4 (P4) and 8 (P8) during acquisition of a sequential reaching task: a) and c) early session one; b and d) late session three. With practice P4 demonstrated increased SH Mean absolute relative phase (MARP) and point-estimation relative phase (PRP) (increased in time spent in anti-phase relationship) and P8 demonstrated a reduction in SH MARP and PRP (increased time spent in in-phase relationship).

middle ranges there were larger DP values or more variability. This relationship was not evident with PRP and the PRP variability measures.

Discussion

For this serial reaching task, we have interpreted the MARP and PRP values cautiously, and propose that values above 100 degrees represent trials where joint coordination by participants who spent more time in anti-phase and values less than 100 degrees represent trials where participants' joint coordination represents an in-phase relationship. Our caution is based on the periods of non-stationary relationships between the joint segments in movement patterns during the serial reaching task, which may limit the interpretation of PRP and MARP values. Both measures appeared to estimate in-phase and anti-phase relationships and distinguished between shoulder-hip and hip-ankle postural coordination in performance of this serial reaching task. Proximal PRP and MARP were highly related and both measures identified when participants used predominately in-phase or anti-phase coordination patterns. In addition, distal PRP and MARP measures classified all the participants' distal postural coordination patterns as predominately anti-phase. Note that we used anatomical angles to calculate the shoulder, hip and ankle displacement instead of segmental angles. The directions of angular displacement across the movement would be different when using segmental angles and cause a different interpretation of relative phase joint relationships than found with our method. The effects of joint relationship on PRP and MARP suggest that these measures may distinguish between proximal and distal patterns of movements.

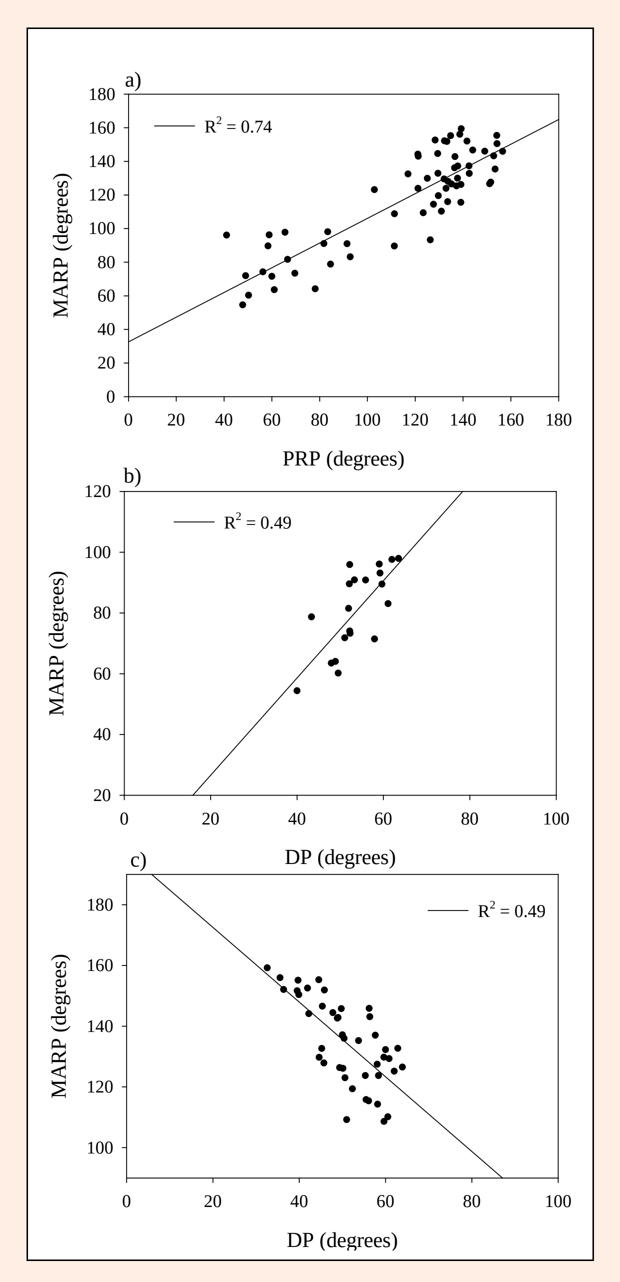

Figure 6. Graphs represents linear relationship between a shoulder-hip (SH) mean absolute relative phase (MARP) and point-estimation relative phase (PRP) values (a), and relationship between SH MARP and DP values when SH MARP values were categorized as < 100° (b) and > 100° (c). R^2 represents the amount of variance explained by the associations.

The fact that practice did not affect MARP or PRP could partially be attributed to individual differences in directional changes of the coordination patterns across practice. For example, participant 4 (Figures 5 a-b) demonstrated increasing MARP and PRP values suggesting increased time spent in anti-phase across practice while participant 8 (Figures 5 c-d) demonstrated decreasing MARP and PRP values suggesting increased time spent in in-phase across practice. Individual variability in postural joint dynamics agrees with the concept that multiple postural configurations are available to support postural stability during reaching (Riccio, 1993). Changes in motor coordination during learning of new skills may be different among individuals (Button et al., 2006) and may relate to the individuals pre-existing coordination dynamics or "intrinsic dynamics" (Kostrubiec et al., 2012). Although we did not examine pre-existing coordination patterns in this study, they have been shown to influence learning of novel postural coordination pattern (Faugloire et al., 2009).

The relative stability of these coordination patterns could be assessed by looking at the variability in the continuous relative phase curves and point-estimations, DP and inter-trial SD of PRP. We found stronger relationships between MARP and DP, than PRP and inter-trial SD of PRP. The relationship between MARP and DP would suggest that there is potential in finding stable in-phase (close to 0 degree) and anti-phase (close to 180 degree) patterns of postural coordination. The variability in the magnitude of change in the MARP and DP may be reflected in an individuals' predisposition to use a specific postural coordination strategy or their responsiveness to changing postural strategies (Faugloire et al., 2006; 2009). During continuous visual tracking tasks, the ranges of the average inter-trial SD of PRP were reported to be between 20 and 30 degrees when hip-ankle coordination were in stable in-phase or anti-phase patterns and greater than 60 degrees when hip-ankle coordination were in unstable patterns (Bardy et al., 2002). The variability measures, DP and inter-trial SD of MARP and PRP, were higher in the serial reaching task (see Table 1) as compared to variability during a visual tracking task. This finding might suggest there are unstable patterns of coordination in the serial task. However, the in-phase and anti-phase coordination modes of a visual tracking task is associated with the frequency of the oscillating task (James, 2014), but movement frequency is less consistent in the serial task. The nature of this serial task with discontinuity of movements and inter-trial transitions between patterns might explain the greater variability as compared to the continuous oscillating nature of a visual tracking task. The values of any relative phase measure and their variability will likely be task dependent.

Considerations for MARP and DP in a serial task

A judicious approach is needed when interpreting MARP and DP values with the performance of a serial reaching task or any task where movement dynamics may be changing. First, important dynamics may be lost when averaging the continuous relative phase curves in either discrete (Figure 2d) or serial tasks (Figure 5). The arm movements in the serial task contained two different amplitudes with starts and stops and the postural responses were often discontinuous. Within any trial, the continuous relative phase curve moved through a greater range of values and contained periods when the joint relationship

Table 2. A comparison of the advantages and disadvantages of MARP, DP and PRP for estimating joint relations during movement tasks.

Measure	Potential Uses	Advantages	Disadvantages
MARP **DP**	• Continuous movements • Discrete movements • Serial movements?	**MARP** • Quantifies (estimates) inter-joint relationships during movements • Averages all relative curve data points • Reflects the whole curve dynamics • Accounts for both displacements and velocities of joint or segment angles **DP** • Quantifies variability across several trials or cycles of movements • Examines the variability along the whole curve or variability of the shape of the curves	• Multiple step calculation • Postural joint movements and positions may require normalization of angular displacements and velocities • Non- stationary relationships more likely seen in serial task; resulting in phase wrapping, e.g. one joint movement and one joint not moving • Phase distortions (phase shifts and phase wrapping) in relative phase curve may distort or bias values • Requires visual inspection and manual corrections for longer movements • Absolute value biases the value away from zero • Redundant values within 360-degree data
PRP **SD of PRP**	• Continuous movements • Serial movements?	**PRP** • Quantifies (estimates) inter-joint relationships during movements • Simple calculation to determine relative phase relationship • Can be used with joint moving through different amplitudes and positions • Eliminates asymmetries and irregularities in the actual motion of a task (Zanone and Kelso, 1992) **Inter-trial SD of PRP** • Quantifies variability across a several periods with in a task. • Measured stability of postural coordination pattern in continuous tasks	• May eliminate important joint relationship dynamics between maximal peaks. • Must have at least two unambiguous maximum or minimum points within the reference angle; decreases utility with discrete movements or if examining movement intervals • Shorter duration tasks may have a small number of reference periods available to calculate **PRP** • Selecting peaks may be difficult within serial tasks: non-sinusoidal signals (Wheat and Glazer, 2006) • Postural movements are often small and gradual resulting in a decrease number of unambiguous points. • Requires visual inspection of point selection. • Redundant values in 360 within degree data

was close to in-phase, anti-phase, and/or transitioning between the two modes. Individuals who used in-phase and anti-phase patterns at different points within the task would have more mid-range values. Any single measure used to estimate a joint relationship over time will have this problem, if the relationships between the segments are changing. One advantage of using MARP in a serial task is that dynamics of the movements may be better captured during a specific phase or step of the task. This could be analogous to using MARP to look at joint relationships during the stance phase of gait (e.g., Kurz and Stergiou, 2002) or a specific range of the movement in a weightlifting task (Hu and Ning, 2015). Although we did not present MARP or DP within each of the 15 movement intervals, the calculations were the averages of the values of the intervals. Analysis of interval MARP may give insight into the changing dynamics at different points in performance of a serial task. An example might be a participant who uses an in- phase shoulder-hip coordination pattern in the early intervals but demonstrated an anti-phase pattern during other intervals (Figure, 5b).

Phase distortions in the continuous relative phase curves were the most frequent problem that occurred during data processing. Corrections for phase shifts were not difficult, but time intensive for long data arrays. Others have noted the need to make corrections for phase shifts when using continuous relative phase data, (e.g. Seay et al, 2011). Phase wrapping was a more notable concern. Continuous relative phase curves that predominately exhibited an anti-phase or in-phase coordination pattern were often changed by phase wrapping because of discontinuity in the movement. Phase wrapping will also bias MARP toward mid-range values and increase DP values. We experienced phase wrapping more often in the distal continuous relative phase curves, which might explain why distal MARP values were lower than PRP values. PRP measures were not as strongly influenced by movement irregularities as MARP measures. Another bias in the MARP calculation is that by taking the absolute value of the relative phase curve any negative number is eliminated, thereby preventing MARP values to cancel out and to equal zero degrees. However, the lack of a zeroing out effect should not eliminate using MARP as a measure of coordination. For example, James (2014) reported stable in-phase postural coordination modes with experimental and simulated relative phase values, ranging between 20-60 degrees.

Considerations when using PRP in a serial task

Selection of the reference peaks was the major problem when calculating PRP for postural joint relationships in a serial reaching task. PRP assumes that the angular displacement time series will appear as quasi-sinusodal movement patterns. Although we saw sinusoidal patterns in the sagittal plane arm movement task, discontinuity in the movements of this serial task decrease the ability to identify point-estimation values for each identified period. In addition, we found that ankle displacements during this task were often very small or gradual, which resulted in difficulty identifying target peaks within some of the reference angle (hip) periods. Figure 4a shows a trial where ankle target peaks were easily identified within a participant's performance and Figure 4b demonstrates a trial where ankle target peaks were hard to identify in a different participants' performance. A similar problem was noted by Oullier and colleagues (2002) when they calculated hip-ankle PRP during a ten second visual tracking task. In the visual tracking task only 4 point-estimations were used to calculate hip-ankle PRP for a trial. When unambiguous peaks could not be identified, reference periods were eliminated from the calculation (Bardy, et al., 2002; Faugloire, et al., 2006; Oullier, et al., 2002). We also eliminated reference periods, and were able to capture between 5 and 7 periods within the serial 17.5 second task. Generally, later in practice, hip and ankle displacements were smaller resulting in more eliminated periods. The limited number of values available to calculate PRP with each trial could affect the PRP and the inter-trial SD of PRP values. High inter-trial variability of PRP was evident in the serial reaching task. We propose that point identification problems as well as task differences between visual tracking and sequential reaching may contribute to the different variability in PRP values in this study.

Although PRP is a much simpler calculation and does not require any manipulation of kinematic data, the elimination of reference periods was a concern. In a multi-step task, PRP measures do not account for what might happen in the periods when point-estimations were eliminated. Consequently, we preferred MARP and DP in the serial reaching task over PRP, because the use of MARP and DP allowed us to capture all the relative phase information across the trial and to examine relative phase within the intervals or steps of the task.

The advantages and disadvantages of using MARP, DP and PRP measures are summarized in Table 2. The limitations in calculating these measures require clear definitions of how the data will be handled for consistency and how to minimize errors and bias in the values. The nature of the serial reaching task may require that qualitative analysis, such as angle-angle plots; accompany the relative phase measures for more comprehensive interpretations of postural coordination. Careful considerations of the nature of a task and the resulting movement patterns are needed to guide the choice of measures used in any analysis. Switching of coordination patterns may be required for stability and task orientation, as the postural system accounts for more dramatic force interactions of the multistep arm movement tasks than during performance of oscillating visual tracking tasks. All the coordination measures may be useful to classify stable and unstable postural movement coordination patterns. However, MARP and DP may be advantageous when analysis of joint relationships across an entire movement is desired, as in discrete movements or during phases of movement. PRP and SD or inter-trial PRP may be more efficient with more continuous tasks where regular cycles of movements can be determined.

Conclusion

We examined the use of different relative phase measures to identify postural coordination patterns during learning of serial reaching tasks. Relative phase measures traditionally used for either discrete or continuous oscillating tasks were challenging when applied to measuring postural coordination during a serial reaching task. This paper describes the methods employed to minimize errors and biases in the relative phase measures and discusses the strengths and limitations of using these measures within the context of a serial reaching task. Although individual differences in postural coordination patterns limited our ability to show group changes during learning of the serial reaching task, MARP and DP showed the potential to identify stable and unstable postural coordination patterns within this task. Appropriate selection of a relative phase measure should consider the nature of the task in relationship to the measures' strengths and limitations.

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Key points

- MARP, DP and PRP measures coordination between segments or joint angles
- Advantages and disadvantages of each measure should be considered in relationship to the performance task
- MARP and DP may capture coordination patterns and stability of the patterns during discrete tasks or phases of movements within a task
- PRP and SD or PRP may capture coordination patterns and stability during continuous oscillating movement tasks.

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