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Time Series Analysis of Postural Responses to Combined Visual Pitch and Support Surface Tilt

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Abstract

The purpose of using time-series analyses is to provide interpretation of information on curves or functions, such as dynamic, biomechanical data. We evaluated the application of one method of time-series analysis for assessing changes in postural responses when exposed to a continuously rotating visual field combined with a tilted support surface. Functional Principal Component Analysis (fPCA) was applied to center of mass (CoM) trajectories collected from 22 young adults (20–39 y.o.) on a fixed surface or following a 3 deg (30°/sec) dorsiflexion tilt of the support surface combined with continuous upward or downward pitch rotation of the visual field at 30 and 45°/sec. The usefulness of this analytical tool is that each curve is treated as a distinct observation by itself, allowing for traditional PCA to be applied to the analysis of curves. Results of the fPCA highlighted 5 distinct time periods in the CoM curves that explained 91% of the variability in the data. These periods in which the young adults altered their CoM in response to visual field motion would not have been identified if we had relied on the onset and offset of the transient disturbance to distinguish responses. Young adults significantly displaced their CoM in response to visual motion over both the period of support surface tilt and while the support surface returned to a neutral position. Our results indicate that fPCA is a viable method when applied to the small but complex changes that emerge in postural data and might allow for a better understanding of time dependent processes occurring with pathology and intervention.

Introduction

Postural research and intervention has traditionally focused on the rapid, transient, automatic responses to a sudden disturbance. To examine these responses, the mechanical system is often reduced to a single degree of freedom of motion with postural control defined by the input/output relations at that body segment [22–24,26]. In addition, estimating CNS recalibration to intersensory conflict has been limited because subjects were either physically constrained [26] or the role of each stimulus was defined by its removal rather than by its action in the presence of other inputs [2,3,25,37]. Human postural control in

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everyday activities, however, involves a continual mix of motion across several segments, including the ankle, knee, and hip [21,30], in response to a multimodal sensory array.

Fluctuations in both sensory information and postural state over time have been shown to influence the automatic responses to a transient disturbance [7,10,35]. Even during quiet stance, the frequency spectrum of center of pressure fluctuates [18,19,31,33] in response to continuous kinematic behavior shifts between the ankle and hip [1,13]. The influence that the composition of the sensory array has on these fluctuations has not yet been identified. If the kinematic resultant of postural tuning during quiet stance is constantly varying, it seems reasonable to hypothesize that the organization of the ongoing postural state can be modified by the available sensory array as well as by the transient mechanical disturbance.

In order to explore how optic flow information that was either conflicting or concurrent with somatosensory feedback influenced postural responses, we have employed a time series analysis known as functional principal component analysis (fPCA). The usefulness of this analytical tool is that functions are fit to the data and then each function is treated as a distinct observation, allowing for traditional principal component analysis (PCA) to be applied to the whole curve. Thus, the output of the fPCA directs us toward the dominant modes of variation around an overall trend function and allows for quantification and statistical analysis across segments of the curve and between experimental conditions. The fPCA has been used successfully to characterize how muscle frequencies change over time in healthy children and children with cerebral palsy [14–17], as well as with changes in handwriting [28,29], evolution of chemical reactions [6] and characterization of gait [4]. We used this method for the direct comparison of various time segments of the postural response to visual field motion.

We applied the fPCA to center of mass (CoM) trajectories of young adults to determine whether this technique would detect how direction and velocity of visual field motion influenced the adaptation of postural responses over time. Responses of young adults were assessed while they were standing on a support surface that tilted and viewing a visual scene that rotated in the same and opposite direction of the surface tilt. With efficacy of fPCA on postural responses established, it will be possible to expand the usefulness of this technique to assess postural variations with pathology and the effects of clinical intervention on daily activities.

Methods

Data Collection

Twenty-two healthy young adults (20–39 yrs, 14 males and 8 females) gave informed consent as approved by the Institutional Review Board at Temple University to participate in this study. Subjects who reported a history of neurological disorders, vision problems, motion sickness, hearing problems, severe to moderate arthritis and limited range of motion were excluded.

Individuals stood on a 3 degree of freedom posture surface (Neurocom International Inc., Clackamas OR) with integrated dual triaxial force plates (AMTI, Watertown, MA) that was located within a 3-wall virtual reality back projection system that has been described previously [5,34]. The visual scene presented as a room with rugs, columns, ceiling and distant horizon (see Figure 1 [11]). Subjects stood comfortably on the support surface with their feet side-by-side at hip width and arms at their sides. Foot position was marked on the support surface and reproduced across trials. Three-dimensional kinematic data from the head, trunk, and lower and upper limbs was collected using Motion Analysis (Santa Rosa, CA) 6-camera infrared Hawk system at 120 Hz and low pass filtered at a cutoff frequency of

4Hz. From the marker displacement, CoM of the body was calculated [39]. Changes in CoM were assessed only in the anterior-posterior direction, which was the direction of largest response to the perturbation.

Each subject completed 12 trials with order randomized. Subjects were asked to maintain an erect posture and look straight ahead. For 6 trials, the support surface was fixed while the visual field either remained dark, was matched to the motion of the head or was simultaneously rotated in upward or downward pitch at velocities of 30 and 45°/sec. In the other 6 trials, 5 sec of quiet stance was followed by a support surface rotation of 3° in dorsiflexion at a velocity of 30°/sec and the same visual field conditions as above. Onset of visual motion and surface tilt was synchronized. The 3° surface tilt was maintained for 30 sec, and then slowly returned to the neutral at a constant velocity of 0.1°/sec over a 30 sec period. In this paper, we focused only on the responses during the tilt trials.

Functional Principal Component Analysis (fPCA)

Qualitative analysis of the CoM data was quantified through fPCA [28,29]. Principal component analysis is a mathematical least squares statistical procedure that transforms a large data set of correlated variables into a smaller number of linear uncorrelated variables called principal components. The first principal component accounts for as much of the variability in the data set as possible, and each succeeding component accounts for the maximum amount of variance that is left. Thus, PCA is an example of a mathematical maximization procedure. The fPCA performs the same operation, converting a large number of correlated variables into a smaller number of principal components. However, in this case, the 'variable' is the functional relationship between the data points rather than the trajectories over time [32].

The first step in performing the fPCA was to generate a basis expansion, which is a curve that best fits the CoM trajectories. This was achieved using a 6th order B-spline with 500 basis functions. The coefficients associated with each function was determined by a least squares fit to minimize error. For these data, the maximum error between the fit of the B-spline and the CoM trajectories was 0.064 indicating that the B-spline fit the data sufficiently well. After this point, the fPCA is similar to the traditional PCA with the exception that the covariance matrix maintains time dependent relationship resulting in loadings (principal components) that are functions. Weights can then be calculated as the integral of the product of the CoM trajectory and loading function over time resulting in a weight for each observation per component. The weights indicate how well the individual CoM trajectory matches this principal component function.

To facilitate interpretation of the fPCA, a varimax rotation [28,29] was used so that the resulting principal components expressed a more focused, descriptive characterization of the variations in the CoM, thereby maximizing differences between the visual conditions. As a result of the varimax rotation, the values are still orthogonal but may no longer be uncorrelated and the percent variances explained may not decrease monotonically [28,29]. Since we were only interested in CoM responses during the combined disturbances, the CoM data were truncated to remove the first 5 sec of quiet stance prior to onset of the stimuli. The fPCA revealed five components in the CoM data that explained 91% of the variance in these data (Fig. 1).

Comparison of traditional PCA and fPCA

To compare results from the two PCA methods, the traditional PCA was applied to the CoM trajectories. In brief, the PCA was performed using the MatLab command 'princomp' on all trajectories (Statistical toolbox 7.0, Mathworks, Natick, MA). Projections of CoM on each

principal component were determined by multiplying the eigenvectors by the raw data resulting in eigencurves [32]. The eigencurves were normalized to the peak to peak range (Fig. 2). A total of 8 components explaining 87% of the total variability was found based on the criterion of keeping eigenvalues ≥ 1 . Further examination revealed that components #6–8 contained mostly noise and were thus not useful in interpreting the data. We ignored these components and used 5 principal components to explain 85% of the variability.

Results from the traditional PCA indicated that component #1 described 66% percent of the data and had a similar shape as the mean of the raw CoM data. Components #2 and 3, however, differed from the raw data in the direction of CoM trajectory. The explanation for this discrepancy is that the first component removed the most common mode in the data. Subsequent components then contained only variations that remained in the data after the first component was removed. If our objective was to find the most common mode of CoM motion arising from the support surface motion, then the traditional PCA would serve. However, our objective was to determine when visual flow caused a shift in responses over time. We cannot use the traditional PCA to investigate this objective because the PCA loadings for each principal component are averaged over the entire trial period [6]. However in the fPCA, time dependence is maintained in the covariance structure and the eigenvalue decomposition results in loading functions that can be used to identify periods that differ due to visual flow.

Statistics

For each functional principal component, the distribution of the weights was assessed with a Shapiro-Wilks statistic to assess normality. This p-value was significant ($p < 0.05$) for all components indicating that the weights were non-normally distributed. Kruskal-Wallis tests were used to assess whether CoM differed between the visual conditions with the weights used as the dependent measure. If significant, Wilcoxon paired test was used to determine differences in the CoM between each visual condition compared to the dark at $p < 0.05$.

Results

Both component #1 and #3 described motion of the CoM during the period of sustained tilt. Component #3 described the initial reaction to the perturbation and component #1 overlapped component #5 somewhat by describing the CoM response starting at 4 sec following onset of the tilt to the end of the tilt period (duration of 26 sec). The remaining two components slightly overlapped in the description of the period that the support surface returned to a neutral position. Component #4 described the CoM response in the first 25 sec of that period and component #2 described the CoM response during the last 10 sec of that period.

Significant differences to visual field motion were found for components # 2, 4 and 5 (Table 1, $p < 0.01$). During pitch upward rotation of the visual field at $30^\circ/\text{sec}$, young adults moved their CoM more posteriorly than when in the dark starting in the last 10 sec of the sustained tilt period and continuing for 25 sec during the period that the support surface returned to neutral (component #5 and #4; $p < 0.03$; Fig 1). When the scene pitched upward at $45^\circ/\text{sec}$, young adults displaced their CoM more posterior than when in the dark during the last 10 sec of the sustained tilt period and continuing for 15 sec during the period that the support surface returned to neutral (component #5; $p < 0.04$).

During pitch downward rotation of the visual field at $30^\circ/\text{sec}$, young adults displaced their CoM forward relative to their position in the dark starting the last 10 sec of the sustained tilt and continuing over the entire period that the support surface returned to neutral

(components #4, #2 and #5; $p < 0.02$). However, no significant changes in CoM were found with pitch downward rotation of the visual field at 45°/sec.

Discussion

Our main finding, that CoM changed over the period containing both the sustained tilt and the return of the surface to neutral, reveals that time-dependent analysis of postural behavior could be meaningful when assessing functional activities. If we had followed a more traditional approach in analyzing these data, we would have most likely separated the response to the transient tilt, the response adaptation to the tilted support surface, and the response following the return of the surface to neutral position [8,9,22,38]. Analyses would then have been performed at a specific recording time within each of these intervals, or as a comparison of the average values. This would have negated the shape of the CoM curve which provides information about the postural control strategies employed. Although the fPCA components were overlapping, the fPCA maintained time-series information that is lost in other studies. In addition, through the fPCA we found that exposure to combined visual motion and surface tilt modified the response behaviors that emerged as the support surface was returning to neutral. The impact of the sensorimotor environment on the return to an upright position has not been focused on in the past.

Postural control is usually studied by examining data over specific time periods based on a priori information about an expected control mechanism or a sensory input change. The literature presents conflicting evidence about response latencies to sensory signals, particularly when perception is involved, that increases the probability of error when deciding how to analyze human behavior. For example, postural responses due to visualvection have been reported to appear approximately 10 seconds after visual field motion [11,27]. But recently, studies have indicated that when visual motion is combined with surface perturbation, responses to visual motion occurred within 2–4 seconds following onset of the combined disturbances [38]. One advantage of the fPCA is that we did not need *a priori* information about when the young adults would shift their responses to visual motion. Thus, we were able to capture the time dependent response changes that would have been lost on an *a priori* method of analysis.

A clear result was that young adults shifted their CoM in the direction of the visual motion with the CoM becoming negative when shifted backwards and positive when moved forward. We were able to detect these shifts by calculating the weights of each component, thereby making it possible to compare responses using standard statistical methods while maintaining the shape of the curve and its time-series evolution. By looking across the shape of the curve we also found that young adults displaced their CoM in response to visual velocity as well as direction. The data suggest that subjects suppressed their response to the visual flow when it was faster and in the direction opposite that of the physical tilt.

We infer from this behavior that the velocity mismatch between the visual field and the physical motion was less compelling when the direction of visual field motion was appropriate for the compensatory response (i.e., when the body pitches backwards the world should move downward). When both visual field velocity and direction did not match that of the physical motion (i.e., when the visual field pitched upward), our subjects responded as observed with a directional mismatch alone [12]. Thus, the fPCA, detected responses in the CoM that were consistent with previous findings, demonstrating that it is a reliable tool for assessing time dependent postural responses.

Although a large amount of variability was explained by the fPCA components, weights for components #1 and 3 did not reach significance. The variability explained by these

components may have captured individual differences in the young adult responses to the sudden tilt (component #3) or in their alignment to a vertical orientation on a tilted surface (component #1) independent of visual motion. Therefore, in assessing variability with the fPCA, we are learning not only how and when individuals respond to visual motion, but also when responses differ within the group over time. With larger sample sizes, we may further parse out sub-groups within our data sample using the information gained from the fPCA. For example, the variability in component #1 may be due to some of the young adults responding to visual motion while another group of young adults may have been relying on somatosensory feedback to align their bodies to the tilted surface and ignoring the visual motion during the sustained tilt [20,36]. We could potentially prove the existence of these sub-groups by applying cluster analysis to the weights from the fPCA if we had larger sample sizes. Differentiating responses within a population may help us better understand how different strategies can be employed to maintain balance and can be useful in assessing postural responses in visually dependent patient populations to identify the most effective interventions.

In conclusion, we consider fPCA to be a powerful tool for describing kinematic changes over time. Our results indicate that fPCA is a potentially useful technique for examining time dependent postural responses because (1) it reveals time periods in the CoM trajectories that may not have been analyzed if the data was arbitrarily separated into time periods, and (2) the technique was able to detect differences in postural responses due to visual field velocity and direction. With these data we have demonstrated that CoM responses of young adults are modulated in relation to the congruence of the velocity and direction of visual flow and support surface perturbation.

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Figure 1. Principal components from the fPCA for CoM trajectories. Black line is the mean CoM and gray lines present the variation that existed across all conditions in the forward (positive) and backwards (negative) directions.

Figure 2.
Eight principal components from a traditional PCA for CoM trajectories.

Table 1

Average (standard deviation) weights of each functional principal component (PC) and visual conditions

Visual condition	PC1	PC2	PC3	PC4	PC5
Dark	3.05	5.00	-0.85	0.57	1.41
	(43.72)	(26.76)	(21.61)	(35.77)	(35.26)
Pitch Down 30°/sec	21.03	-29.34	1.42	27.71	-30.90
	(44.31)	(39.17)	(23.48)	(31.82)	(40.65)
Pitch Down 45°/sec	13.87	-10.57	-1.37	15.45	-20.02
	(57.69)	(46.65)	(24.74)	(57.03)	(62.80)
Pitch Up 30°/sec	-19.45	18.22	3.42	-25.04	28.32
	(53.63)	(44.53)	(28.25)	(43.22)	(50.79)
Pitch Up 45°/sec	-18.85	9.26	1.26	-13.86	23.09
	(68.12)	(50.56)	(34.06)	(57.94)	(55.88)