ABSTRACT

NONLINEAR ANALYSIS OF PROPRIOCEPTIVE TRAINING INDUCED CHANGES IN POSTURAL CONTROL ON A DYNAMIC SURFACE

by Joshua Lewis Haworth

This research seeks to describe the postural sway performance of participants during quiet stance on a dynamic surface, longitudinally throughout a balance training program. A nonlinear method of data processing was presented, along with traditional linear statistics, as an effective movement descriptor. COP was measured on a compliant surface atop a force plate, during each laboratory visit. Results show no change in COP range, change in variability only in the anteroposterior direction, and reductions in both velocity and LyE in the mediolateral and anteroposterior directions. Reduced LyE values indicate a more periodic (self-similar) structure within the COP path. It appears that the participants were able to develop a more calculated approach to the maintenance of balance by moving both more slowly and with a more regular movement pattern. Support for the use of both a dynamic surface and a nonlinear analysis for the evaluation of postural sway has been provided.
NONLINEAR ANALYSIS OF PROPRIOCEPTIVE TRAINING INDUCED CHANGES IN
POSTURAL CONTROL ON A DYNAMIC SURFACE

A Thesis

Submitted to the
Faculty of Miami University
in partial fulfillment of
the requirements for the degree of
Masters of Science
Department of Kinesiology and Health
by
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Miami University
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2008

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Introduction

Proprioceptive training is a common methodology used to enhance an individual’s ability to maintain stability within their environment. This training methodology is used across many levels of practice including athletic performance enhancement, injury rehabilitation, and general personal training settings. Included are both simple and complex exercises that are designed to challenge the trainee’s current level of proficiency at maintaining stability in both stationary and dynamic tasks. Of specific target for proprioceptive training is the development and enhancement of body position awareness through control of afferent feedback and knowledge of joint position during activity (McGuine & Keene, 2003). It is proposed that improving these neuromuscular interactions will result in improvement in postural control, described as behavior intended to preserve body segment coordination with no subsequent loss of balance (Smart & Smith, 2001). Example tasks in proprioceptive training include one legged stance, stance with eyes closed, a variety of stances with atypical body positions (i.e. Yoga and Pilates), and stances challenged by compliant surfaces and other apparatuses (i.e. DynaDisc, BOSU, and Thera-band). Additionally, these tasks can be performed as both static and dynamic techniques, and dual tasks can be added to increase the level of difficulty. In all cases, it is intended that by placing an individual in a pseudo novel postural environment, within safe training conditions, they will be able to learn strategies that will later transfer to enhanced postural performance within unpredictable environments. Ultimately, reductions in performance failures (stumbles or falls) are anticipated, leading in the end to declined risk of injury.

At present, there is a mixture of evidence in the literature regarding the effectiveness of proprioceptive training on the enhancement of postural control. Some studies that have been conducted with healthy populations (Hoffman & Payne, 1995; Kovacs, Birmingham, Forwell, & Litchfield, 2004; Yaggie & Campbell, 2006) and pathologic populations (Gauffin, Troop, & Odenrick, 1988; Kidgell, Horvath, Jackson, & Seymour, 2007) indicate the benefits of training. However, there are also studies (Bernier & Perrin, 1998; Cox, Lephart, & Irrgang, 1993; Riemann, Caggiano-Tray, & Lephart, 2003; Hess, Joyce, Arnold, & Gansneder, 2001) that report unclear findings to this regard. One consistent factor in these studies is the use of center of pressure (COP) as a means to track postural sway performance. COP represents the point of application of the resultant ground reaction force acting on the support surface (Le Veau, 1992). Tracking this point across time allows for the analysis of characteristics of postural control during stance (Cavanaugh, Guskiewicz, Stergiou, 2005). Herein lays a critical point, and the point of difference among the aforementioned studies. How should these signals be processed to provide researchers and clinicians with output variables that fully, yet simply, represent the postural activity, thus providing insight to the underlying mechanism(s) of control and comparative indicators of function/dysfunction of these systems?

Proposed solutions include the use of summary statistics such as postural sway range, velocity, variability, etc. However, none of these methods seem yet to have been able to fully characterize the events occurring during postural control performance (Palmieri, Ingersoll, Stone, Krause, 2002). In fact, it may come to be that none of them specifically are able to do such, and some combination of analysis techniques may result
as a best set of measures. As well, novel descriptors may need development in order to satisfy this need.

From reviewing the literature, it seems that these linear methods fail, and essentially do not even attempt, to elucidate the meaning of variability found within postural sway data. Commonly, variability is measured as the standard deviation about the mean position of COP (Hoffman & Payne, 1995; Cavanaugh et al., 2005). When considered in time series data this measure has been taken to represent system noise, and thus not representative as a meaningful descriptor regarding posture and its control.

Recently, though, applications of dynamic systems theory have demonstrated that the contrast may be true, in that describing the characteristics of these inconsistencies in COP position may provide information about movement control previously unattainable from traditional analyses (Stergiou, 2004). In light of this, many researchers have begun to apply the tools provided by nonlinear dynamics and in doing so have provided novel and effective descriptors of this movement system (Megrot, Bardy, Dietrich, 2002; Schmidt and Riley, 2005; Cavanaugh et al., 2005). In addition to simply describing quantities of the movement (i.e. range, average velocity, variability, etc.) these techniques provide the capacity to evaluate different qualities of the movement system (i.e. periodicity, self-similarity, long-range correlation, etc.). It is thought that the use of nonlinear analyses may not only expand our ability to understand the dynamics of postural control, but may also add another level of sensitivity to the evaluation of pathologies and in the assessment of the effectiveness of rehabilitation therapies, i.e. proprioceptive training (Bernier & Perrin, 1998; Hess et al., 2001).

For example, Cavanaugh et al. (2005) used nonlinear analysis of COP data to describe postural control following low grade concussions sustained during athletic events. After five days post-concussion, results showed that traditional measures of postural control (sway velocity, variability, and path length) had returned to baseline, however, nonlinear analysis indicated an ongoing functional change to postural control as a result of the concussion. Another study by Pellechia and Shockley (2005) studied the effects of cognitive load on postural control and compared results from traditional (postural sway range and velocity) and nonlinear analyses. Traditional statistical methods supported a well-known finding that increases in cognitive load result in decreased postural control (as indicated by increased sway velocity and range). However, nonlinear analysis showed that the dynamic pattern of sway became more periodic and regular as a product of increased cognitive load; indicating that although range and velocity of sway increased with added cognitive load, the pattern of postural motion became more regular. These findings were interpreted to mean that participants may be evoking a qualitatively different postural strategy that is adaptive and functional in order to preserve postural control when attention was diverted (Pellechia & Shockley, 2005).

Another important factor to be considered regarding postural performance is the theoretical capacity of an individual to control posture within their environment. It seems there is an implicit supposition that individuals are able to control all environments with which they interact. However, what of dynamic surfaces? For instance, many training and rehabilitation programs include exercises using surfaces that exhibit continuously changing responsive properties, i.e. DynaDisc (Kidgell et al., 2007; Hoffman & Payne, 1995). As well, function in real situations requires constant adaptability to changing environmental conditions. From the classic motor control paradigm, it is believed that
posture is controlled through the application of intentional movement strategies via preprogrammed or dynamically generated continuous feedback (Park, Horak, & Kuo, 2004), which seek to minimize movement output error. It is posited that these movements are performed with the attempt to maintain COP about a static point attractor; i.e. “perfect” balance would exhibit no sway characteristics. Park et al. (2004) discuss that this system is rich with multiple heterogenic feedback, leaving one to wonder whether an extensively novel environment might overwhelm the ability of the system to respond to environmental manipulations. This proposed strategy may work quite well within known, fixed, or moderately changing environments, but could leave much room for error when balance is required within unknown or continuously changing environments. This research leaves open the question of how the postural control system is able to organize strategies for the maintenance of balance in truly dynamic situations.

Additionally, much of the research regarding postural control in a dynamic environment has been performed using experimentally controlled environmental oscillation frequencies; mostly focused on the emergence of relative phasing between hip and ankle control strategies for maintaining balance across varieties of vision and surface manipulations (Marin, Bardy, Baumberger, Fluckiger, & Stoffregen, 1998; Bardy, Marin, Bootsma, & Stoffregen, 1999; Buchanan & Horak, 2001). Although the affordance of researcher control over the environment allows for some critical evaluation of possible control strategies employed by participants, it does not ideally mimic realistic postural situations. It may be that this experimental control needs to be relinquished, by utilizing uncontrollable responsive support surfaces, such that a more true depiction of events occurring during dynamic postural performance may be evaluated. The combined use of a true dynamic surface and nonlinear analysis may prove beneficial to understanding the characteristics of postural performance, and perhaps control, during an activity that more closely mimics real situations. Using this approach pair could lead to better observation and evaluation of the strategies enacted by postural control systems, i.e. adaptability and environmental exploration that leads to behavioral maintenance and transitions (Kelso, 1995).

Thus it was the goal of this study to investigate participant’s response to a balance training program through nonlinear analysis of postural sway data taken during quiet stance on a dynamic surface. Comparisons were made regarding the use of traditional statistics versus nonlinear methods, specifically Lyapunov Exponent (LyE), used as performance measures. To clarify, it is not expected that nonlinear analysis might replace traditional descriptors, but instead may add levels of quality to the interpretations of the data. Furthermore, the daily measures were assessed, longitudinally, to determine the time course of changes within postural sway performance. In other words, did persons adapt to training rapidly, within 3-6 training sessions, or were continued performance changes seen throughout the six week program?
Methods

Participants
Eighteen healthy, physically active individuals were selected for participation in this study (5 male, 13 female; age (yrs) = 20.24 ± 0.90; body mass (kg) = 66.05 ± 11.78). Prior to participation, an initial description of the research was provided to potential participants, after which informed consent and a medical history questionnaire were completed by each individual. Individuals were excluded from participation if they identified as having an orthopedic injury to the lower extremity within the last 6 months, chronic ankle instability, or cardiovascular disease. All participants completed the six week balance training program, including data collections, without complication or lack of adherence to program guidelines (including full attendance and completion of all exercises within each session). All procedures involved with this study were reviewed and approved by Miami University's Institutional Review Board prior to initiation of the study.

Procedures
All activities associated with this project were conducted in the Motor Behavior Laboratory, including COP measures and balance training sessions. Participants were invited to engage in a balance training program designed to specifically target whole body stability within a variety of stance conditions. The program consisted of three training visits per week for six weeks, totaling eighteen (18) training sessions. Testing included the collection of one 30 second measure of COP time series data on a compliant surface, DynaDisc-Plus; conducted prior to training during each laboratory visit.

COP Measures
Postural sway for each participant was measured during each of the 18 visits. Center of Pressure (COP) time series data were collected using an in-ground force plate (Bertec, USA, model #6090-15) on top of which was placed a compliant surface; DynaDisc-Plus. Each test included one thirty second trial; sampled at 100Hz. Participants were requested to stand, barefoot, in a quiet bipedal stance atop the DynaDisc, with arms folded across the chest. In order to minimize inter-trial variation due to wandering gaze, a 2x2 inch visual target was placed at eye level, at a distance one meter from the participant. Prior to initiation of data collection, the verbal instructions, “please stand as still and quiet as possible, and keep your gaze on the target” were delivered.

Balance training
Each participant completed eighteen sessions of a balance training program, three per week for six weeks. Each of these sessions lasted approximately 30 minutes and included a single trial of COP data collection (as described above) followed by a series of eight training exercises (each including four levels of increasing difficulty) designed to maintain a safe but challenging experience during each set. A Licensed and Certified Athletic Trainer was consulted in the development of the training program, to ensure the safety and applicability of all exercises. All sessions were supervised by at least one member of the primary research staff. In addition, all individual exercises were monitored by a member of the research staff positioned proximate to the participant such that
physical assistance could be provided to avoid falls. Charts were kept for each participant detailing a subjective performance evaluation and level of progression within each exercise for each day. Exercise difficulty progression was determined by evaluation of participant performance by the research staff, as trained by a Licensed and Certified Athletic Trainer, combined with participant’s willingness to attempt a more difficult version of the task. Table 1 presents a list of the nine exercises performed, and the level of difficulty reached by participants by program end.

For each exercise, the level of difficulty was enhanced by introducing simple modifications to the original task. Examples include performance of the task with eyes closed (i.e. Single Leg Stance and BOSU), performance of the task on a compliant surface (i.e. Squat & Reach and Steamboats), and/or introduction of a dual task while performing the original exercise (i.e. BOSU and Forward/Side Hops). In all cases, the goal of the training exercises was to keep the participant in a nearly unstable state throughout the exercise, determined by self report and visual assessment by the research staff. A full description of the exercises used, and description and order of difficulty progression, can be obtained by contacting the authors of this study.

Data Analysis

Traditional versus Nonlinear Statistics

Traditional Descriptive Statistics

A 10Hz low-pass filter with dual pass was applied to each set of COP time series data prior to analysis using traditional measures, as was separation of the data into mediolateral (ML) and anteroposterior (AP) data subsets. Each subset was subsequently analyzed using a macro created in Microsoft Excel 2003 constructed to output values of COP range, average velocity, and variability.

• range (cm) was defined as the difference of minimum COP position from maximum

\[
\text{COP range} = \text{COP}_{\text{max}} - \text{COP}_{\text{min}}
\]

• average velocity (cm/s) was defined as total path length of COP divided by trial duration

\[
\text{Average velocity} = \frac{\text{COP}_{\text{path}}}{\text{trial duration}}
\]

• and variability (cm) was defined as the Standard Deviation of COP position

\[
\text{Variability} = \text{SDEV} (\text{COP position})
\]

Lyapunov Exponent (LyE)

For reasons discussed by Buzzi, Stergiou, Kurz, Hageman, & Heidel (2003), it was decided that data for nonlinear analysis would be left unfiltered. In summary of their rationale, the goal of nonlinear analysis is to interpret variability within a system apart from that which could be resonant noise due to measurement methods. It is expected that
the consistency of data collection across all trials, by using the same equipment and standardized procedures, has minimized variability from non-movement system sources.

Nonlinear methods draw on the redevelopment of data from a single dimension time series into a corresponding multidimensional state space in which the $n^{th}$ dimensional space matches the true dimension of the system. Doing such allows analysis of the dynamics of a complex system from collection of more feasible measurements. This process requires the use of an appropriate number of embedding dimensions, the number of time delayed copies of the data set, for reconstruction. In this study, embedding dimension was determined by processing a set of randomly selected trials through a False Nearest Neighbor (FNN) program available with Visual Recurrence Analysis Software (v. 4.9), and was determined to be eight for the given data.

Lyapunov Exponent (LyE) was calculated for each data subset (see above) using the Chaos Data Analyzer (CDA) Software (Sprott & Rowlands, 1999). LyE is a nonlinear method used to describe local variability within a data set. LyE is calculated as the slope of the average logarithmic divergence of neighboring trajectories (Wolf et al. 1985), describing the rate of divergence of nearby trajectories within a state space (Stergiou, Buzzi, Kurz, Heidel, 2005). To conduct this analysis, the CDA software requires the setting of three parameters; Embedding Dimension ($D$), Accuracy ($A$), and Number ($N$). As discussed, $D$ was determined to be eight for the given data. $A$ refers to the relative accuracy of the data and defines the point below which noise is expected to dominate; set to $10^4$ (the default setting). $N$ refers to the number of sample intervals over which each pair of points in the state space is followed before a new pair is chosen; set to two.

Using LyE, postural sway trial data would be able to be determined as more or less chaotic relative to other collected trials. Generally, positive values for LyE indicate chaotic/unstable systems. However, the nearer to zero the value of LyE approaches, the more periodic/invariant the data is said to be. Although this analysis allows for the relative description of the given data as chaotic/periodic, insufficient resources for validation and comparison exist to fully claim an interpretation representing the absolute chaotic nature of the system. The goal of this study stands instead to make statements about the comparative variability among COP trials.

**Analysis**

Values for all four variables (range, variability, velocity, and LyE) in both ML and AP directions, were averaged across all participants for each respective day of collection (1-18), and plotted against trial number using an Excel chart for qualitative analysis. Values were then collapsed by 3 day groups, representing each week, for further analysis. A one way repeated measure MANOVA was used to determine whether changes occurred across the six weeks. Paired t-tests were used *post hoc* to locate where these changes occurred throughout the six weeks. MANOVA and t-tests were performed using SPSS software v.16.0. Alpha level $p < 0.05$ was used for analyses.


Results

Results of the pre-post comparisons t-tests show (Figure 1A) no change in COP range in the ML direction (0.13 cm, p = .481) and the AP (0.48 cm, p = .139); (Figure 1B) significant changes (reductions) in COP velocity in both the ML (0.38 m/s, p = .0003) and the AP (0.74 m/s, p = 3.5E-6); (Figure 1C) no changes in COP variability in the ML (0.02 cm, p = .491) but significant changes in the AP (0.15 cm, p = .042); and (Figure 1D) significant changes (reductions) in COP LyE in the ML (0.009278, p = .001) and the AP (0.013611, p = .0031) (see Figure 1).

Results of the repeated measures MANOVA indicate significant differences in each variable (range, variability, velocity, and LyE) across the six weeks of training, in both the ML (Figure 2) and AP (Figure 3) directions. In both directions, COP range (ML: F_{5,85} = 4.065, P < 0.002; AP: F_{5,85} = 2.825, P < 0.021) and variability (ML: F_{4.185,71.145} = 4.789, P < 0.002; AP: F_{5,85} = 2.357, P < 0.047) follow a quadratic trend, whereas velocity (ML: F_{5,85} = 8.366, P < 0.000; AP: F_{5,85} = 12.806, P < 0.000) and LyE (ML: F_{5,85} = 6.098, P < 0.000; AP: F_{3.211,54.593} = 5.886, P < 0.001) follow a linear trend. A Huyh-Feldt correction factor was used where Mauchly’s test for sphericity indicated a violation of assumptions, as was the case for variability in the ML direction (Mauchly’s W = 0.154; χ^2 = 28.26, P < 0.014) and LyE in the AP (Mauchly’s W = 0.144; χ^2 = 29.3, P < 0.010). In both cases, the correction yielded significant results as presented above.

Results of the post hoc paired t-tests are presented in table 2, and indicate where changes in each variable occur throughout the six weeks of training.
Discussion

The purpose of this study was to evaluate the postural sway performance of participants during quiet stance on a dynamic surface throughout a six week balance training program. One of the goals of this evaluation includes determination of movement characteristics during the application of postural control while interacting with a movement responsive surface. Additionally, a nonlinear method of data processing was presented, along with traditional linear statistics, as an effective movement descriptor.

It was found that postural sway performance was affected by participation in the balance training program in some, but not all, of the collected measures. There was no change in COP range; however the velocities associated with these movements were decreased. Variability, as measured by the traditional standard deviation of COP position, increased in the anteroposterior direction, but was unchanged in the mediolateral direction. LyE values decreased in both anteroposterior and mediolateral directions, indicating a more periodic/deterministic (self-similar) structure within the COP path. Taken together, it appears that the participants were able to develop a more calculated approach to the maintenance of balance during interactions with a responsive dynamic surface by moving both more slowly and with a more regular movement pattern.

What is interesting, here, is that the behaviors exhibited by the participants in this study seem to mimic that which has been described of pathological populations, and oppose that which has been described in highly proficient balance performance (Schmidt and Riley, 2005). Additionally, these results contrast almost exactly with those found in another paper from our group. Strang, Haworth, Hieronymus, Smart, & Walsh (In Review) measured postural sway performance during quiet stance on solid ground. In opposition to the results of this study, it was found that the same training program elicited completely opposite changes in postural sway measures; range, velocity, variability, and LyE. The challenge here is to make sense of the results of the present study in consideration with the aforementioned results from other studies. It is offered that the mixed results may come, not from differences in the status of the postural control system, but instead that postural performance is directly influenced by task constraints.

The issue with variability and periodicity in postural sway performance revolves around an issue of learning and adaptability within known and dynamic environments. Variability of COP position during postural performance may actually be beneficial during attempts to control motor behavior. The traditional idea is that variability around a point attractor symbolizes behavioral error; however this claim is currently inundated with empirical evidence to the contrary. In fact the opposite is posited to be true in that variability of COP position represents the “functional range” within which a motor behavior can be executed properly. In place of the traditional measure of COP position (standard deviation) to describe movement variability, the measure of the regularity of motor behavior (i.e. periodicity, self-similarity, long-range correlation, etc.) seems to better explicate the presence or absence of error. This discussion has been presented by a number of articles that support understanding postural performance as a limit cycle and not as a point attractor system (Carroll & Freedman, 1993; Cavanaugh et al, 2005; Pellecchia & Shockley, 2005).

A rudimentary example of this is presented here, considering the tossing of a set of dice. If one were to throw ten die, it would be expected that the value of each would
differ a certain amount from that of the others, and from the mean of the set (variability within the system). However, if the same ten die were thrown with continued replication of results, i.e. each die turns up the same every time, then high self similarity is found in the same system that presents with potentially high variability. In terms of postural performance, it seems that high variability (related to adaptability to dynamic environments) coupled with high periodicity (production of the same ‘set’ of behavior) would result in the most optimal performance.

Returning, now, to the results of this study, it appears that the balance training program was highly effective in enhancing the participant’s postural performance. COP behavior presents as more periodic, with increased movement variability in the anteroposterior direction. Functionally, the individuals were able to retain the ability to adapt to changes within environmental interactions through movement variability, but also produce motor output more consistently indicating increased control.

Evidence from the literature supports this observation. Studies including participants having motor impairments such as Parkinson’s disease show that variability decreases with severity of disease progression (Schmidt and Riley, 2005), thus these individuals seem to have lost an amount of adaptability to environmental changes. As well, these patients show increased periodicity. In this case, the decrease in adaptability would certainly override the reproducibility of motor behavior, in the same way that consistently reporting the wrong answer is consistently wrong. In contrast, studies involving athletes touted to be highly balance proficient (ballet dancers; Schmit, Regis, Riley, 2005) demonstrate low periodicity with maintained variability. In this case, periodicity enables the performance of postural control while high movement variability allows the individual to continue to investigate their environmental surroundings.

In the current study, the level of control needed to sufficiently perform the task is actually learned to be less than initially expected, and thus control of behavior is relaxed throughout the learning process. How can it be explained, though, that the same learning sequence (six week training program) elicits seemingly opposite effects in terms of postural performance?

The answer to this is proposed to lie in the concurrent importance of variability and regularity previously discussed. Moreover, task demands appear to strongly determine the motor behavior that is produced. It seems that the control system responsible for postural performance is able to respond to environmental constraints such as the variations in task difficulty found from differences in surface type (somatosensory feedback). When conditions demand adaptability, movement variability is maintained. Similarly, it seems that the control system is able to enhance its awareness of the level of control necessary for the prevention of dysfunctional performance.

For example, during bipedal upright stance it is know that the body undergoes continuous sway even without the influence of external perturbations (Collins and Deluca, 1994). This constant sway is not thought to reflect decreased postural control but instead has been interpreted to indicate that posture is an oscillatory system and thus postural control may be thought of as the optimal regulation of an oscillatory behavior (Cavanaugh et al., 2005; Pellechia & Shockley, 2005). Simply put, traditional measures cannot capture the dynamics of an oscillatory behavior because they suppress the time evolving dynamics of rhythmic patterns and assume that any deviation from zero equilibrium reflects instability (Carroll & Freedman, 1993; Collins &DeLuca, 1994).
The theoretical concern derives from a common assumption made by most traditional theories of postural control that optimal postural control occurs when postural movements are held to a minimum (Nashner & McCollum, 1985). The problem with this assumption is that the body undergoes continuous postural sway even without the influence of external perturbations or disease (Collins and Deluca, 1994). Thus, it appears that postural control may be better described as an oscillatory limit cycle rather than a static point attractor (Cavanaugh et al., 2005; Pellecchia & Shockley, 2005). Or put another way, postural control may be better described as the optimal regulation of a rhythmic coordination rather than attempt to move the body to resting or static point. This creates a problem for traditional descriptive statistics that are typically measures of central tendency. Measures of central tendency are only relevant in reference to some mean and its variance (e.g. - avg. velocity, range, median frequency, etc). However, when one is attempting to describe a continuous flow or rhythm (e.g., postural sway) it becomes unclear what the mean really means? In other words, measures of central tendency, which may be adequate for describing some basic characteristics of postural movements, could be considered inadequate for capturing the time-evolving dynamics of rhythmic coordination reflected in postural sway (Carello & Moreno, 2005; Carroll & Freedman, 1993; Cavanaugh et al., 2005; Palmeri et al., 2002; Pellecchia & Shockley, 2005).

Thus it seems that even with the same preparatory training, motor behavior within different environments is able to respond to the constraints presented by the environment. The results of this study, coupled with the results of Strang et al. (In Review), support this suggestion. It is, however, also possible that no specific control function is active during this process. Instead, postural control could be of a passive nature regarding interactive responses. In other words, the mechanism driving the behavior is far less interested in the specific motor activity required, but is actually focused solely on goal achievement. This suggests that the coupling of afferent feedback to motor output may function sans control per say, but is actually an emergent and self-organizing system.

It is seemingly apparent, then, that task constraints can be found highly responsible for the exhibition of behavior. Even the presence of perceived constraints has been shown to effect motor actualization. Dingwell, Cusumano, Cavanaugh, and Sternad (2001) present evidence that treadmill walking presents as more regular than is continuous over ground walking. Their study suggests a caution for the use of treadmill walking in the study of gait dynamics, but also brings to attention the need to consider the manner by which task constraints control motor activity.
Conclusion

This research has provided evidence that individuals do respond to balance training with changes in postural sway. Measures of range and variability were shown to decrease during the first two weeks of training, and then subsequently return to week one values. Measures of velocity and LyE were shown to decrease in a linear fashion throughout all six weeks of training. These changes in performance can be explained as a result of changing strategies enacted by the postural control system. At the outset, postural performance exhibits a developing rigidity in all four measured variables. In sum, individuals tend to move less within a smaller range, at a slower rate and with a more consistent pattern of movement. After two weeks of experience within the dynamic environment, training, the motor control system seems to become more relaxed in its control of range and variability. This is thought to occur due to the benefit to the system of increased exploratory movement within the environment, thus maximizing the information gathering capacity from which future movement is planned. At the same time, velocity continues to decrease as movement continues to become more self-similar. These qualities signify the benefit of increased processing time and planning of future movements. Slower movements result in slower response by the environment to those actions. More regular movement patterns elicit responses by the environment that are more predictable, and thus allow greater potential that the subsequently planned movement will be appropriate for the individual within the resulting environment.

The question that remains is what might have been seen had the training program been of ten week duration, or even longer. Would range and variability have remained at week one values, or continue to increase? Would velocity and LyE continue to decrease, or would there be a flooring effect at some point that would have become evident with a longer training and data collection period? What is clear, however, is that training effects postural performance, and from this it can be inferred that changes are resultant due to the adaptability of the postural control system to dynamic environments, through training.

In addition, this study has provided support for both the use of nonlinear analysis of postural sway data and the use of dynamic environments during the collection of COP data. Nonlinear analysis has been shown to describe COP data in a fresh manner, adding interpretations of quality of the movement pattern to the traditionally captured quantities of the movement. By using a compliant surface during data collection, evidence has been revealed that points toward the nature of postural control as being task dependant and thus potentially an emergent, self-organizing system.
Limitations

The combined use of a true dynamic surface and nonlinear analysis technique has provided interesting empirical results regarding the characteristics of postural sway. However, the methods employed were restricted to the collection of kinetic COP data. It may prove additionally interesting to repeat this study with the inclusion of kinematic and EMG data collection. This could allow further insight into how changes in movement strategy are produced; i.e. joint movements and associated muscular activity. Additionally, tracking changes in the measures of COP during stance, throughout training, using other conditions such as on a non-compliant surface, with eyes closed, and with an added cognitive load, may add further support for the claim that postural control is task dependant. As well, in light of the results of the repeated measures analysis of range and variability, a longer training duration is recommended for any future investigation that seeks to track changes in postural sway in a longitudinal fashion.
References


Strang, Haworth, Hieronymus, Smart, & Walsh (2008) In Review


Tables

Table 1 – Frequency distribution of the balance training group. Frequency reflects the highest level achieved by each participant over the six-week training period.

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<td>*</td>
<td>18</td>
</tr>
<tr>
<td>Double Leg BOSU</td>
<td>*</td>
<td>*</td>
<td>4</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Single Leg Squat &amp; Reach</td>
<td>*</td>
<td>*</td>
<td>3</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Skateboard</td>
<td>2</td>
<td>6</td>
<td>8</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Steamboats</td>
<td>*</td>
<td>*</td>
<td>4</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>Forward hop</td>
<td>*</td>
<td>*</td>
<td>4</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Side hop</td>
<td>*</td>
<td>*</td>
<td>4</td>
<td>14</td>
<td></td>
</tr>
</tbody>
</table>

Table 2 – Results of post hoc paired t-tests to determine changes throughout six weeks

<table>
<thead>
<tr>
<th>Pair (weeks)</th>
<th>Range X</th>
<th>Range Y</th>
<th>Variability X</th>
<th>Variability Y</th>
<th>Velocity X</th>
<th>Velocity Y</th>
<th>LyE X</th>
<th>LyE Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>0.020*</td>
<td>0.005*</td>
<td>0.003*</td>
<td>0.178</td>
<td>0.005*</td>
<td>0.003*</td>
<td>0.484</td>
<td>0.402</td>
</tr>
<tr>
<td>1-3</td>
<td>0.001*</td>
<td>0.257</td>
<td>0.000*</td>
<td>0.119</td>
<td>0.000*</td>
<td>0.001*</td>
<td>0.009*</td>
<td>0.392</td>
</tr>
<tr>
<td>1-4</td>
<td>0.019*</td>
<td>0.520</td>
<td>0.040*</td>
<td>0.454</td>
<td>0.004*</td>
<td>0.000*</td>
<td>0.018*</td>
<td>0.162</td>
</tr>
<tr>
<td>1-5</td>
<td>0.085</td>
<td>0.531</td>
<td>0.046*</td>
<td>0.729</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.003*</td>
<td>0.029*</td>
</tr>
<tr>
<td>1-6</td>
<td>0.210</td>
<td>0.948</td>
<td>0.092</td>
<td>0.273</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.000*</td>
<td>0.011*</td>
</tr>
<tr>
<td>2-3</td>
<td>0.748</td>
<td>0.053</td>
<td>0.498</td>
<td>0.752</td>
<td>0.208</td>
<td>0.229</td>
<td>0.064</td>
<td>0.111</td>
</tr>
<tr>
<td>2-4</td>
<td>0.982</td>
<td>0.411</td>
<td>0.548</td>
<td>0.601</td>
<td>0.284</td>
<td>0.034*</td>
<td>0.103</td>
<td>0.045*</td>
</tr>
<tr>
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<td>0.276</td>
<td>0.049*</td>
<td>0.274</td>
<td>0.139</td>
<td>0.081</td>
<td>0.005*</td>
<td>0.023*</td>
<td>0.008*</td>
</tr>
<tr>
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<td>0.028*</td>
<td>0.012*</td>
<td>0.055</td>
<td>0.026*</td>
<td>0.032*</td>
<td>0.011*</td>
<td>0.003*</td>
<td>0.003*</td>
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<tr>
<td>3-4</td>
<td>0.705</td>
<td>0.197</td>
<td>0.172</td>
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<td>0.828</td>
<td>0.082</td>
<td>0.619</td>
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<tr>
<td>3-5</td>
<td>0.148</td>
<td>0.505</td>
<td>0.034*</td>
<td>0.043*</td>
<td>0.349</td>
<td>0.005*</td>
<td>0.132</td>
<td>0.021*</td>
</tr>
<tr>
<td>3-6</td>
<td>0.013*</td>
<td>0.329</td>
<td>0.003*</td>
<td>0.012*</td>
<td>0.095</td>
<td>0.018*</td>
<td>0.131</td>
<td>0.002*</td>
</tr>
<tr>
<td>4-5</td>
<td>0.291</td>
<td>0.167</td>
<td>0.582</td>
<td>0.342</td>
<td>0.242</td>
<td>0.504</td>
<td>0.111</td>
<td>0.099</td>
</tr>
<tr>
<td>4-6</td>
<td>0.043*</td>
<td>0.056</td>
<td>0.181</td>
<td>0.047*</td>
<td>0.095</td>
<td>0.430</td>
<td>0.046*</td>
<td>0.025*</td>
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<tr>
<td>5-6</td>
<td>0.293</td>
<td>0.531</td>
<td>0.297</td>
<td>0.468*</td>
<td>0.423</td>
<td>0.702</td>
<td>0.941</td>
<td>0.600</td>
</tr>
</tbody>
</table>

* indicates significant difference, p < 0.05
Figures

Figure 1: Comparison of day 1 to day 18 for each variable in both ML and AP direction; A) COP Range, B) COP Velocity, C) COP Variability, and D) COP LyE.

*indicates significance, p< 0.05
Figure 2: Week-wise analysis of variables in the mediolateral direction; A) COP Range, B) COP Velocity, C) COP Variability, and D) COP LyE.

Weeks where difference is significant are listed in ( ), p< 0.05
Figure 3: Week-wise analysis of variables in the anteroposterior direction; A) COP Range, B) COP Velocity, C) COP Variability, and D) COP LyE.

Weeks where difference is significant are listed in (), p< 0.05