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MOVEMENT VARIABILITY DURING ISOMETRIC FORCE TRACKING AND QUIET STANCE

By

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Variability in human motor performance is an area of study that has many unanswered questions. Nearly every system of the human body has variability while it performs its functions. Simply looking at heart rate and respiratory rate shows the variable function of two of the main systems of the human body (circulatory and respiratory systems). Additional variance comes from the degrees of freedom (DOF) of the human body. DOF consist of joints, muscles, and the body’s nervous system. These combine with the external forces of the movement to produce limitless patterns and outcomes. A person has a difficult undertaking of controlling their DOF to perform a task consistently with little variability. While this complexity can be looked at as a negative, there are also benefits that this allows a person, such as, the ability to adapt to a change in a given task. This complexity, allows the use of non-linear techniques to look at human movement variability (Harbourne & Stergiou, 2009; Goldberger, Amaral, Hausdorff, Ivanov, Peng, et al., 2002). Unlike typical static measurements, non-linear techniques are dynamic measures and reveal more about the state of the system as a whole than do static measures. A large amount of physiological functions can produce non-linear dynamical signals. The output from insulin secretion, respiration, sleep-wake cycles, electrical activity in the autonomic nervous system and cortex are just a few examples (Cavanaugh, Guskiewicz, & Stergiou, 2005). Examples of instruments that collect dynamic measurements include, but are not limited to: electrocardiogram (ECG), electromyography (EMG), and electroencephalogram. A clinician can analyze this continuous dynamic data to quantify changes in behavior over time and to determine the quality of the time-series.
The importance of using non-linear measurement to evaluate different abnormalities has become a growing field of study (Pincus & Goldberger, 1994; Walleczek, 2000). In 1929, homeostasis was introduced and described as “coordinated physiological arrangements of attaining constancy” in a biological organism. It was believed that the human body was regulated at a constant level and fought to maintain those levels by simply counteracting the oscillation to that level. Traditionally, increased variability in a body’s regulatory system was looked at as a pathological abnormality. It is now believed that the contrary is true, that a biological system is regulated by sustained oscillatory dynamics (Walleczek, 2000). These sustained oscillatory dynamics are present in the vital functions of the body (e.g. heart rate, respiratory rate, hormone secretion). They are also prevailing in the functions of daily life (e.g. postural sway, visual-motor tracking, patterns of motor movements). With this new knowledge, it may be more accurate to refer to homeostasis as homeodynamics. A person’s health has long been associated with regularity and stability, but plenty of research has shown now that healthy function is also associated with chaotic, irregular dynamics. Subsequently, if healthy function is associated with chaos, then pathology can be linked to loss of irregularity or more regularity over time (Walleczek, 2000).

Pincus & Goldberger (1994) showed an example of increased regularity being associated with pathology by examining the heart rate tracing data of two infants. One infant was considered a normal healthy child, while the other had experienced a life-threatening event, also called an aborted sudden infant death syndrome (SIDS), one-week prior. The data showed that, while both had normal
mean heart rate levels and heart rate standard deviations (overall variability), they differed on the regularity of their heart rate. By using the measurement of approximate entropy (ApEn), which measures the regularity of a dynamic time-series (see figure 1; Cavanaugh, Guskiewicz, & Stergiou, 2005), they showed that the SIDS infant had a heart rate that was more regular (less complex) than the healthy infant (Harbourne & Stergiou, 2009).

Another study showed the effects a concussion has on heart rate variability (Gall, Parkhouse, & Goodman, 2004) and how a concussion could cause neuroautonomic cardiovascular dysfunction (NCD). They stated there was no definite reason this occurred, but they believed the concussion could cause a neuroautonomic pathway disruption. The disruption would lead to an uncoupling of the autonomic and cardiovascular systems, causing problems with the body’s natural ability to regulate its heart rate within its current environment. The first example of the body’s natural ability is the sympathetic nervous system, also know as the “fight or flight” response will cause the heart rate to rise, and help aid the blood to the muscles, helping the body to either “fight or flight”. The second example is the parasympathetic system will essentially do the opposite; it will decrease heart rate and send the blood to the internal organs to aid in their functions (Acharya, Joseph, Kannathal, Lim, & Suri, 2006). The study showed that the damage from the concussion affected the body’s ability to facilitate these automatic processes causing a less variable and more regular heart rate. These examples further suggest that less complex (more regular) signals can be a sign of pathology.
The concept of non-linear dynamics has also been used to examine changes in postural control. In the past, it was thought that a person’s ability to balance better than others was due to their ability to maintain a static, non-moving, stance easier and longer than their peers. This idea may be inconsistent with the finding of more current postural control tests. Center of pressure (COP) is a variable defined as the application point of the resultant ground reaction force vector acting on a surface. The study of COP can give understanding into a person’s postural stability by looking at the movement of their COP during a given time. Studies are now showing that the variability in COP during quiet standing is a favorable attribute. What was once thought of as noise is now being better evaluated, to give us more concise answers to how the body regulates COP and balance. While large amplitude oscillations that are outside the body’s base of support are still considered unfavorable, smaller sustained oscillations are considered favorable for a healthy individual (Cavanaugh, Guskiewicz, & Stergiou, 2005; Walleczek, 2000). Looking at a study done by Schmit et al. (2006) that examined the COP data of people diagnosed with Parkinson’s disease (PD) shows evidence of this. The researchers in the study
compared data using recurrence quantification analysis (RQA) to evaluate the COP dynamics of the PD patients. RQA is an analysis tool that assesses the non-linear dynamics in a complex data set. The researchers found that while the PD patients had more overall variability with their COP, they also showed a more predictable dynamic pattern. The use of the dynamic RQA measurement showed that the PD patients COP data was more regular and less complex, and helped the researchers to better understand the pathology (Schmit, Riley, Dalvi, Sahay, Shear, et al., 2006).

Increased knowledge of non-linear dynamics in postural control might aid diagnostic capability for physicians and healthcare professionals. The improved awareness of mild traumatic brain injuries (mTBI), and their long-lasting side effects, in the last few years has raised the need for an evaluation and diagnostic tool to be used on the sidelines of sporting events, clinics, and hospitals. Early research has shown that a previously concussed athlete will show an increase in the regularity of their COP oscillations (Cavanaugh, Guskiewicz, Giuliani, Marshall, Mercer, & Stergiou, 2005). Using this knowledge along with other diagnostic tools may better help clinicians successfully diagnose patients with concussion and better determine when they are fully recovered.

Research has also been done to look at the non-linear dynamics of other tasks, such as, visual-motor tracking (VMT) (Ofori, Samson, & Sosnoff, 2010; Sosnoff & Newell, 2007). As was the case with COP, VMT had differences in regularity when comparing a group of healthier people to a less healthy group. The researchers stated that previous evidence shows that, as adults reach the later years in their life, decrements in visuomotor processing start to take affect. Ofori et al (2010)
compared a group of healthy college age individuals (M = 21.9) to a group of healthy elderly individuals (M = 71) using a visual-motor tracking task. Using their index finger pressed against a force transducer, they were asked to maintain a constant force matching a line depicted on a computer screen. The results showed that, while the elderly group had more variability, the college-aged group had a higher ApEn value, indicating greater irregularity. This again shows that aging, much like neurological deficits, decreased the regularity of dynamic control. Additionally, preliminary research done in the Motor Control lab at Utah State University has also shown decreased ApEn values in subjects with history of concussion.

Research shows the body's capacity to act as a variable and non-regular system is an important component to identifying many deficits. Advancing knowledge of non-linear dynamics could possibly lead to improving diagnostic tools for many different and dissimilar conditions (e.g., concussion, Parkinson's disease, Diabetes). While too much regularity in a dynamic signal is not advantageous, the comparison of non-linear dynamics within an individual over different tasks (e.g., visual motor control and postural control) has not been examined. If the structure of variability we see in human behavior is reflective of the state of the system as a whole (just as inflammation in the body is general indicator of health), the same structure should be reflected in different "control systems" (e.g., visual motor control and postural control) (Walleczek, J., 2000). Therefore, we predict that there will be a correlation within individuals of the non-linear characteristics of performance in a postural stability and a visual-motor tracking task.
Methods

Participants

Forty participants aged 18-28 were recruited for participation in this experiment. The mean age was 22.2±2.4 years. Participants were not paid. Participants were recruited by word of mouth via the department and laboratory websites, personal recruitment, and via the undergraduate research participant pool (SONA). Prior to the study, participants were required to sign an informed consent form approved by the university Institutional Review Board.

Apparatuses and Tasks

Participants were seated at a table with an 18” Dell laptop or an 18” computer monitor positioned in front of him or her on the table. In front of the LCD monitor, there was an ASL load cell (diameter 1.27cm) mounted on the right side of a wooden block so that it is normal to the table and on the right hand side of the participant. The participant positioned his/her right hand so that it was pronated, resting to the right of the load cell with only the right index finger coming into contact with the load cell and all other fingers resting in a neutral position on the table. In order to produce a recordable abduction/adduction force using the index finger alone against the load cell, each participant was instructed to position his or her index finger so that the lateral side of the distal inter-phalangeal joint was in contact with the load cell. Data was sampled at 100 Hz.

During the trials, the target path was represented in red (1 pixel wide) and a larger (4 pixel) red dot represented the instantaneous position of the target path. As a participant began to produce force, a white target path appeared on the
monitor representative of the participant’s force output. Both the red target path and the white time-series moved across the monitor in real time during the trial. Participants performed three trials with full visual feedback (a trace of the white line was visible on the screen) and three trials with no visual feedback (white line disappeared from the screen after 3 seconds).

Upon completion of the force tracking protocol, participants were asked to complete a static balance assessment. During the test session, participants were asked to perform a double leg stance with their eyes open and eyes closed. Thirty seconds of kinetic data, used to compute postural sway measurements, was then acquired using a force plate (Bertec Corporation, model FP4060-10-2000, Columbus, OH) and recorded with AcqKnowledge 4.0 data acquisition software (Biopac Systems, Inc., Goleta, CA; sample rate 100 Hz). The force platform and acquisition hardware was calibrated according to manufacture guidelines. Data collection was repeated three times for each condition with a 20-30 s rest between trials. The duration of the stance and the number of trials chosen was based on previous research that reported improved reliability of center of pressure (COP) measurements with these parameters (Ruhe, Fejer, & Walker, 2010).

**Procedures**

**Force Tracking.** To begin, the participants’ maximal voluntary contraction (MVC) was obtained. The participant was instructed to produce a maximal abduction force against the load cell using their right index finger during 3 trials, each 5 s in duration. The MVC was calculated as the average of the maximal force produced during each of the 3 trials.
After the MVC was determined, each participant performed 1 practice trial to familiarize him or herself with the task.

After the practice trials, there were three trials where the subject had full vision and three trials with no-vision. The target path (red) was a constant line centered at 10% of a participant’s MVC. Each trial lasted 30 seconds, and there were a total of 6 trials. The root mean square error (RMSE) was presented to the participant on the monitor at the conclusion of each trial, and indicated the average difference of the participant’s force output time-series from the target path.

For each trial, the participant was instructed to abduct and adduct the index finger while in contact with the load cell so as to produce a line that matches the target path on the monitor. Abducting the index finger caused the force output time-series to move upward on the screen while adducting the index finger caused the force output time-series to move downward on the screen. Each participant was told to try to match the output time-series as precisely as possible to the target path by matching the pathway target and minimizing the error of force output from it.

**Balance Task.** During the testing session, participants were asked to complete six balance trials (three eyes open and three eyes closed), each lasting 30s, on a force platform. Each participant was given the verbal cue “hands on hips...stand as still as possible” immediately prior to triggering the 30s trial. Participants were then instructed to focus on a black and white dot placed at eye level about 2m from the edge of the force plate for the eyes open condition. For the eyes closed condition, participants were instructed to focus on the dot until the trial began, and then instructed to close their eyes for the duration of the trial. Tape was used to
place target marks on the force plate surface to insure consistency of foot placement, minimizing variability in the base of support across conditions.

**Data Analysis**

The present design considers dependent variables reflecting both local and global performance. Local tracking performance was assessed by the root mean square error (RMSE) for each trial. Smaller RMSE scores indicated that the participant’s output time-series was, on average, closer to the target path. Approximate entropy (ApEn) between force output and the target path was used to evaluate the long-range/characteristics of tracking. Smaller values of approximate entropy indicated more regularity in force output. Regularity of the time series (ApEn) was also analyzed. The data analyzed for each trial did not include the first 4 s or the last 1 s of the trial. The significant p-value was less than 0.05 for all statistics.

Static balance kinetic data was recorded and analyzed using MATLAB. The root mean squared error for both ML and AP sway as well as the time series of the distance (in three dimensional space) from the mean COP were calculated. COPx represented ML movement, and the COPy represented AP movement. These measures are also referred to as mean distance in the literature (Prieto et al., 1996). Dependent measures were analyzed over the entirety of the COP time series. Regularity of the COP time series (ApEn) was also analyzed.

**Results**

ApEn values were calculated for the VMT task and for anterior-posterior (AP) and medial-lateral (ML) directions and for the distance from mean COP of the
balance task. Pearson product-moment correlations were computed on participants’ ApEn values for VMT and postural sway in the AP (CoPy) and ML (CoPx) direction, and distance from mean COP for both full vision and no-vision conditions. The main prediction of VMT and COP ApEn values correlating was not supported. Correlations were observed between all postural sway measures and between the vision and non-vision VMT trials. A positive correlation was also shown for force tracking between the vision and non-vision trials. There were no correlations shown between any trials of the balance task and VMT.

<table>
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<th>Quiet Stance</th>
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<td></td>
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<tr>
<td>distCOP no vis</td>
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<td>-0.15</td>
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*vis = full vision condition, no vis = condition with no visual feedback/eyes closed, CoPy = the center of pressure in the y dimension, CoPx = the center of pressure in the x dimension, distCOP = the timeseries of the distance of the COP from the mean COP in three dimensional space*

For the root mean squared error, there was also no correlation seen between any of the postural sway and the force tracking tasks. There were correlations shown between center of pressure in the x dimension (CoPx) and center of pressure in the y dimension (CoPy) during quiet stance. These correlations were shown in both vision and no-vision tasks. Additionally, correlations were shown between both
COPx and COPy when compared with the time-series of the distance of the COP from the mean COP in three-dimensional space (distCOP).

Descriptive statistics are shown in table 3. ApEn was higher for force tracking tasks \( (F(1,3) = 136.13, p = .001) \). In addition, the mean frequency in postural sway was slower than the mean frequency for force tracking \( (F(1,3) = 248.97, p = .0006) \).
Discussion

The aim of this study was to examine the relationship between the non-linear structure of two different motor tasks. A relationship between the non-linearity of force tracking and quiet stance could indicate that non-linear measures capture the state of the motor system as a whole. Participants performed a visual motor tracking task, as well as quiet stance. The non-linear measure of ApEn served as a non-linear measure of regularity. While correlations were detected within vision and non-vision tasks, no correlations were observed between modalities. The lack of correlation between the isometric force tracking task output and the center of pressure output could be due to several things. One reason could be that non-linear measures of performance are specific to the modality and do not reflect the state of the whole system. For instance, the output of the finger in a visual motor tracking task will not look to be the same over time as the output of the whole body as it...
stands quietly (Gurses & Celik, 2013). Postural sway relies on more degrees of freedom (DOF) than finger force production to maintain balance due to the multiple joints used. The vast amount of muscles, bones, and joints used to maintain balance allows for larger assortment of possible output. The VMT task only relied on a single joint, which greatly decreased DOF compared to the balancing task, decreasing the amount of possible output patterns (Hsu, 2014). The discrepancy between the two tasks could also be due to the specificity of motor abilities hypothesis (Magill, & Anderson, 2007). For example, a person could have the ability to perform well at hitting a baseball, but they show little ability at kicking a soccer ball. This would be the opposite of the general motor abilities hypothesis that states skills are highly related. The general motor abilities hypothesis has not been well proven with research while specificity of motor abilities has had better scientific evidence supporting it (Magill, & Anderson, 2007).

Another reason for a lack of correlation between tasks could be a difference in time scale. The 30s sampling duration for the balancing task, while widely used in COP data collection, might have been too short to fully capture the complexity of quiet stance. Research has shown that a sample duration of 60s or more might be more appropriate to analyze the data (Carpenter, Frank, Winter, & Peysar, 2001). The higher mean frequency of isometric force tracking supports the notion that patterns of output may look different over longer time scales (see Figures 2, 3, & 4). For instance, the patterns of variability for postural sway may only look similar to those of force tracking if looked at over a longer duration of time (hence capturing the smaller time-scale changes in relation to the larger ones). In other words, the
same patterns may emerge, but over different timescales, thus leading to a low correlation when looked at over the same time scale. It is possible that further research done with longer sample duration, which could better match-up timing scales, could show a correlation between VMT and postural sway.

Figure 2. Output for one trial of the VMT task with vision

Figure 3. Output for one trial of COPx with vision
From our current research, we have concluded that, the use of ApEn to analyze COP data and VMT data can be an effective tool to study human function and behavior. Since research has shown entropy to be a good dynamical measure (Ramdani, Seigle, Lagarde, Bouchara, & Bernard, 2009), the demand for a single examination tool to observe the system as a whole should call for additional research to see if any correlations are seen between human functions. Walleczek (2000) discussed the possible need for the definitional change of homeostasis to homeodynamics. While our study did not find the possible global characteristics of homeodynamics, we did observe the fluctuating nature of the human system.
References


