TIME-TO-CONTACT DEMONSTRATES MODULATIONS OF POSTURAL CONTROL DURING A DYNAMIC LOWER EXTREMITY TASK

Undergraduate Honors Thesis

By

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2012

Undergraduate Honors Research Examination Committee Approval

[Signature]

Dr. Ajit MW Chaudhari, Advisor
ABSTRACT

Postural control deficits are associated with increased risk of loss of balance and potential injury. To assess for balance deficits and increased injury risk, there is a need to evaluate postural control during dynamic activities. Analysis during dynamic activities could assess if an individual’s ability to control their posture is a fixed condition or if it is dependent on the demands of a task. Time to contact (TtC) detects instantaneous modifications in postural control during dynamic tasks by estimating the time for the center of pressure, given its instantaneous trajectory, to move outside the base of support. The purpose of this study was to evaluate changes in postural control during a dynamic lower extremity task using TtC analysis. 3D motion capture with a force plate was used to evaluate 47 athletes performing the Star Excursion Balance Test. TtC was calculated for 27 valid trials per stance leg. For each trial, the time from the toe leaving the force plate to the toe touching the floor at the maximum reach distance was divided into five epochs of equal duration. TtC was averaged over each epoch. Differences in TtC were evaluated with an unbalanced mixed effects ANOVA and post-hoc Tukey’s HSD comparisons. Epoch was a significant main effect (p<0.001), with significantly different TtC between all epochs (p=0.001). Increasing TtC in later epochs suggests a higher demand for postural control when the task becomes more challenging as the subject’s reaching foot extends further from the body. No significant differences in TtC were present for either stance leg or reach direction. Average normalized reach distances were compared to average TtC during Epoch 5 by direction using a Pearson’s correlation analysis. A very weak correlation was found in the anterior direction (ρ = -0.317, p = 0.032), suggesting individuals modulate their postural
control based on the demands of a task. Future work is necessary to evaluate how TtC relates to other facets of postural control, such as flexibility and strength.
ACKNOWLEDGEMENTS

I am profoundly grateful for the many people who have played a part in the completion of this thesis. First and foremost, I must thank my advisor Dr. Ajit Chaudhari for giving me the opportunity to work in his lab for the last two and a half years. My accomplishments would not have been possible without his guidance and support. I have had the opportunity to experience, learn, and achieve more as an undergraduate than I could have dreamed of because of his confidence in my abilities and I cannot fully express in words how thankful I am to have worked under his advisement.

I would like to thank Dr. Joshua Cotter for allowing me to join the mouthguard study and the many, many hours he spent collecting data. A special thank you to Dr. Jimmy Onate for helping me understand and appreciate the clinical applications of my research, as well as for his continual support and encouragement. I owe a big thank you to Dr. Rob Siston for his mentorship and support. I greatly appreciate his interest in both me and my work and for allowing me to participate in his honors research class in the mechanical engineering department.

I especially want to extend a huge thank you to Steve Jamison for his endless patience and constant support. I greatly appreciate each and every time he stepped away from his own work to answer a question or help me fix a problem in Vicon or MATLAB. More importantly, I cannot thank him enough for helping pull me through times of stress and doubt with words of encouragement and moments of laughter.

I would also like to thank the Ohio State University for their financial support of my undergraduate education. In addition, I want to acknowledge Makkar Athletics, Inc. for funding the mouthguard study.
I also owe a big thank you to the members of the MAP lab for all the advice and support they have given me throughout the many stages of this work. Finally, I want to thank my family and friends for providing shoulders to cry on during the difficult times and celebrating with me in my accomplishments. I would not be here without their unending love and support.
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CHAPTER 1 INTRODUCTION

1.1 Motivation

Human beings carry out a wide variety of dynamic activities during their daily lives. Throughout a movement and even while standing, humans are in dynamic, rather than static, equilibrium (Green 1978). Dynamic equilibrium is the maintenance of control over the body segments during movement to prevent falling (Howe 2001). Balance is essential to successfully completing a task, and, thus, skilled movements are dependent upon an individual’s ability to maintain equilibrium and a stable posture in a variety of positions and under many conditions (Davies 1985). If an individual is incapable of controlling their posture throughout an activity, they are likely to experience a fall and are at risk of incurring injuries associated with falls, as well as other injuries such as ankle sprains (McGuine 2000) and second anterior cruciate ligament tears (Paterno 2010).

To better evaluate and treat individuals with musculoskeletal pathologies, biomechanical abnormalities, a loss of proprioception, and impaired neuromuscular control systems, it is necessary to understand the mechanisms and strategies by which humans control their posture during dynamic tasks. To successfully complete the dynamic activities of daily life, it may be necessary to modify the degree of postural control exerted during the course of the task. Analysis of postural control during dynamic tasks could provide insight into whether an individual is capable of adjusting their control over their posture as the demands of a task change or if the level of control is held constant throughout the task. Therefore, this research aims to determine how healthy individuals modulate their posture throughout a dynamic balancing test.
1.2 Postural Control

1.2.1 Background

Posture is the configuration, position, or alignment of the body joints and limbs (Duarte 2010; Thibodeau & Patton 1993). Balance is the state of the body being in equilibrium (Galley & Forster 1987). Therefore, posture is the result of balancing each body part with respect to the other body parts (Howe 2001). The postural control system maintains the equilibrium of the body (Duarte 2010) by acquiring input from the motor, nervous and sensory systems. Physiological mechanisms from each of these systems can inform the body of a compromise in posture, providing a warning for the potential of undesired movement, allowing the postural control system to prevent the body from losing balance (Howe 2001). The postural control system uses two primary strategies to prevent a loss of balance: compensatory and anticipatory (Pollock 2000). A compensatory strategy is the body’s automatic postural response (APR) to sensory feedback. An anticipatory postural adjustment (APA) can occur when the body predicts a threat to balance (Ghez 2000).

On earth, the force of gravity is constantly acting on the body. Therefore, to maintain an upright position, the body must constantly counter this force and other external and internal forces “by reversing its reactions in response to the direction of the force” (Howe 2001). This results in the postural sway reaction, the constant swaying of the body. Postural sway occurs even during quiet standing, meaning the body is never truly still. A particular posture is therefore a momentary suspension of movement since the body, and thus posture, is in a constant state of change (Bobath 2001).
As stated earlier, an individual is in a constant state of postural sway, thus the position of the body’s center of mass moves in space, requiring the body to respond to counter this displacement. The neuromuscular response to both the displacement of the center of mass and the instantaneous position of the center of mass itself dictates the location of the resultant vector of the ground reaction forces. This location is known as the body’s center of pressure (CoP). The CoP is the most common variable used to evaluate postural control (Duarte2010). An individual’s posture can be quantitatively assessed during a “static,” quiet standing task or during a dynamic activity by collecting two-dimensional position data of the center of pressure using a force plate. Thus, it is possible to evaluate an individual’s postural control by tracking the movement of the CoP over time.

“Good” posture is difficult to define and may be dependent on the goal of the task trying to be accomplished. A good posture may be the position that requires minimal energy input, strains the ligaments, bones, and joints the least, or maintains the center of pressure within the base of support” (Thibodeau & Patton 1993). For the purposes of this research, posture will be evaluated based on the relationship between the position of the CoP and the boundaries of the base of support. The base of support is determined by the area established by the body’s points of contact with the ground, typically the feet. Therefore to maintain balance, the lower limbs must be able to support the body on the base of support and be capable of responding to unanticipated perturbations (Stein 1982).

1.2.2 Traditional Postural Stability Measures using Center of Pressure Measurements

Traditional measures of postural stability quantify the amount of postural sway in a body by relying on a single averaged or overall value of CoP motion over an extended period of quiet
standing. Such measures include mean and maximum CoP excursion, CoP velocity, CoP area, and CoP standard deviation (Hertel 2006a; Ross 2009). These measures have been shown to be effective for evaluating an individual’s ability to minimize their postural sway during static tests. Postural sway has been correlated with sensorimotor deficits which can cause balance impairments (Hughes 1996). Previous research has shown traditional CoP measures to be useful tools for discriminating between functionally stable and unstable ankles during static balance tasks (Ross 2009), as well as assessing standing capability in individuals with spinal cord injuries (Gillette 2002) and age-related differences in postural sway during quiet standing (Kalisch 2011).

Conventionally, these traditional measures quantify postural control using a single value to represent an entire trial. As previously noted, an individual’s CoP is constantly moving, even during quiet standing. Therefore, using a single measure of CoP motion may not be sufficient to fully capture how an individual modulates their postural control during a given task, particularly a dynamic activity.

1.3 Time to Contact

Postural time to contact (TtC) is an alternative CoP measure which represents the time, typically measured in milliseconds, it would take the CoP to move outside the base of support given its current position, velocity, and acceleration (Slobounov 1997). Figure 1 depicts an instantaneous trajectory of the CoP contacting one side of the base of support. The trajectory is shown in blue, the CoP is represented as a black dot, and the base of support is defined by the five black lines outlining the foot. The time required for the CoP to travel along the trajectory and contact the base of support is the TtC. Therefore, a lower TtC indicates that the postural
control system has less time to make a correction in posture before potentially experiencing a loss of balance. By evaluating TtC at each frame in a trial, it is possible to track temporal changes in postural control through the course of a trial. Because TtC quantifies postural control at each frame, it allows for detection of instantaneous modifications in postural stability during more dynamic tasks (Haddad 2010). Thus, TtC can distinguish between periods of increased and decreased postural control within a task (Hertel 2006b).

![Figure 1: Instantaneous trajectory (blue line) of the CoP within the base of support](image)

1.4 Existing Research using Time to Contact

Previous studies using TtC to evaluate postural control during quiet single leg stance suggest that TtC may be capable of capturing differences in functional performance that traditional measures cannot evaluate (Hertel 2006b; Hertel 2007). Based on a study of several different postural control measures conducted in a healthy population, Hertel et al. showed that while traditional postural control measurements and TtC had similar reliability, correlations between traditional measures and TtC were not consistent. The authors propose that this finding
implies TtC assesses different aspects of postural control than traditional measures (Hertel 2006b).

To further assess the utility of TtC to quantify postural control, Haddad et al. used TtC to investigate changes in postural control during a dynamic upper extremity task. Participants stood comfortably with both feet on a force plate and picked a block off a table and then pushed it through either a large or small hole positioned at shoulder height and arm’s length (Haddad 2010). Changes in TtC within each trial were determined by normalizing each time series to 100 data points and averaging TtC data over epochs of 10 data points. Results showed that TtC was longer in the later epochs of the trial as the demand for precision increased while the subjects fit the block through the hole. Furthermore, subjects had a longer TtC when fitting the block through a smaller opening, suggesting that they maintained larger margins of stability when the task required greater precision.

In the same study, Haddad et al also compared TtC data to traditional measures of CoP. The standard deviation of the CoP in the anterior-posterior (AP) and medial-lateral (ML) directions and CoP displacement in the AP direction (the principal direction of the movement) were calculated over the entire trial. In contrast with TtC, no differences were observed between the large and small hole for the traditional measures. The authors concluded from these results that TtC is more sensitive to adjustments in postural stability because TtC uses temporal components of CoP movement, velocity and acceleration, not incorporated in the traditional measurements they evaluated.
1.5 Objectives

While postural control has been quantified during quiet standing and dynamic upper extremity tasks, no study has evaluated postural stability during dynamic lower extremity activities. Therefore, the purpose of this project was to determine if TtC analysis would capture differences in postural control during a dynamic balance test. This work specifically investigates how individuals’ postural control changes throughout the task and if task dependent differences in postural control would be observed during TtC analysis. Additionally, this research investigates if a correlation exists between TtC and the clinical measure of the balance task performed.

1.6 Organization

The procedures for data collection and analysis are described in Chapter 2. This includes a detailed description of the methods and rationale for the balance test analyzed in this thesis. The results of the analysis are reported in Chapter 3 and further discussed in Chapter 4. Chapter 5 includes a summary of the thesis as well as a discussion of the limitations of this work and suggestions for future directions for this research.

CHAPTER 2 DATA COLLECTION

2.1 Origin of Data Set

The data analyzed for this work was collected as part of a protocol that investigated the influence of mouthguards on performance in agility and balance tasks. This protocol was approved by the Institutional Review Board (IRB) at The Ohio State University.
2.2 Subject Recruitment and Screening

Subjects were recruited through fliers posted around the community, online advertisements, and contacts with local sporting groups and recreational and sporting classes. Interested individuals were directed to a secure online survey to answer screening questions and provide contact information. Subjects were required to be between the ages of 18 and 59 years of age with greater than two years of current involvement in a sport in which they competed at least once per year. Subjects regularly trained more than three times a week with a weekly training time of greater than six hours for three months prior to testing. Individuals experiencing any pain that limited movement, wearing a cardiac pacemaker, diagnosed with cancer or known to be pregnant were excluded from this study. Prior to all testing, all subjects provided IRB-approved informed consent.

A total of 47 subjects (39 male, 8 female) were recruited for this study. Subject demographics are presented in Table 1.

Table 1: Subject Demographics (n=47, 39 male, 8 female)

<table>
<thead>
<tr>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs)</td>
<td>22.89</td>
</tr>
<tr>
<td>Height (m)</td>
<td>1.75</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>74.80</td>
</tr>
<tr>
<td>BMI</td>
<td>24.13</td>
</tr>
</tbody>
</table>

2.3 Motion Capture Instrumentation

Eight Vicon MX-F40 motion capture cameras (Vicon, Los Angeles, CA) were used to collect kinematic data. Forty-seven retro-reflective markers were applied to the subject’s skin using two-sided toupee tape. The markers were placed according to a modified version of
Vicon’s Plug-In Gait model (Figure 2) with added markers for the chin, the base of the skull, and the 1st toes. Four 4060-10 Bertec force plates (Bertec, Columbus, OH) embedded in the floor were used to collect ground reaction force data. All data were collected using Vicon Nexus software (Vicon, Los Angeles, CA). The cameras and force plates were calibrated prior to testing each day to minimize instrument error.

Figure 2: Plug-in-Gait marker placement (LifeModeler 2010)

2.4 Experimental Procedure

The research protocol consisted of two separate sessions. During the first session, a licensed dentist fit each subject for two lower jaw mouthguards: a traditional boil and bite mouthguard (Shockdoctor Gravity 2 STC Mouthguard™) and a custom-fitted mouthguard based
on neuromuscular dentistry (Pure Power Mouthguard Elite™). After completing this session, subjects completed a second online survey to gather additional information on their athletic and training history as well as their previous injury status.

During the second session, motion capture was used to collect kinematic and kinetic data of the subjects performing four agility and balance tests: the Functional Movement Screen (Cook 2006a, Cook 2006b), the Star Excursion Balance Test (SEBT)(Plisky 2006), Single Leg Landing, and the Level Belt Test (Chaudhari 2011). Data collected during the SEBT were analyzed for this thesis. The SEBT is discussed in further detail in Section 2.4.1.

At the beginning of the testing session, subject demographics, including height, weight, and limb dimensions, were recorded. The reflective markers were then placed on the subject. A static calibration trial was collected before beginning the tests. The subject performed each of the four tests under three conditions for a total of twelve tests. The three testing conditions consisted of the subject wearing the custom-fitted mouthguard, the boil and bite mouthguard, and no mouthguard. The subject and the staff member administering the tests were blinded to which mouthguard was in use. The subject was not able to see or handle the mouthguard. The mouthguard was inserted and removed by a second staff member using nitrile gloves. The order of the tests was randomized for each subject and an order sheet of the randomization was created by computer prior to the testing session. The second staff member was the only individual to handle this randomization sheet.

2.4.1 Star Excursion Balance Test

The SEBT is a clinical balance test that assesses postural control by challenging an individual’s proprioception, strength and flexibility (Hertel 2006a). The test consists of a series
of lower extremity reaching tasks, requiring an individual to stand on one foot while reaching with their other foot as far as possible in one of 8 different directions. Longer reach distances suggest better functional performance due to the increased demand on the postural and neuromuscular-control systems (Earl 2001). Thus, a further reach distance requires a combination of better stability, strength, and flexibility of the stance limb (Hertel 2000).

The SEBT was chosen because it is more challenging than traditional balance tests and therefore may be more appropriate for healthy, athletic populations. Previous work shows the SEBT is capable of identifying functional performance deficits indicative of lower extremity pathology (Earl 2001; Hertel 2000; Gribble 2004; Olmstead 2002). Moreover, SEBT reach distance measures have been shown to be reliable predictors of lower extremity injury (Plisky 2006) and detectors of individuals with chronic ankle instability (Olmsted 2002), indicating the SEBT provides a sufficient challenge to discriminate within athletic populations.

Because the SEBT has been shown to be an effective screening tool for lower extremity injury risk, it is important that the test take minimal time to be clinically practical. Therefore, the SEBT has been simplified from its original 8 reaching directions. In one study, factor analysis revealed that reach distance measurement from the posteromedial direction alone was sufficient to identify individuals with chronic ankle instability (Hertel 2006a). Additionally, Plisky et al found that the composite of three of the reach directions (anterior, posteromedial, and posterolateral) and reach distance asymmetry in the anterior direction predicted lower extremity injury in high school basketball players (Plisky 2006). Therefore, the SEBT can be performed using just three of the reach directions: anterior, posterolateral, and posteromedial (Plisky 2009).

Subjects performed 4 practice trials in each of the 3 directions (Figure 3) per leg. Previous work has shown that normalized maximum reach distance stabilizes after
approximately 4 trials (Robinson 2008b). Subjects were asked to lightly tap the most distal part of their foot on the floor at maximum reach and return in a controlled manner to the start position with both feet on the force plate. Subjects performed the SEBT barefoot. For the duration of the test individuals were not permitted to elevate their stance foot heel or take their hands off their hips (Gribble 2004). Constraining the stance foot heel increases the importance of flexibility in ankle dorsiflexion range of motion, particularly during anterior reach (Hoch 2011). Furthermore, the importance of flexibility at the proximal joints is increased due to the constraint at the ankle (Robinson 2008a). The hands-on-hips requirement limits the use of the upper extremities to aid in maintaining balance during the task. These task constraints also increase the standardization of techniques utilized in completing the task, thus potentially reducing subject-to-subject variability and learning effects.

Following the practice trials, three valid trials in each of the three directions per stance leg were recorded for each of the three mouthguard conditions, for a total of 27 trials per stance leg for every subject, or 2538 total trials. A trial was considered invalid and repeated if hands came off hips, the stance heel became elevated, the reach toe was not tapped lightly, or if any portion of the movement was performed in an uncontrolled manner.
Figure 3: Star Excursion Balance Test reach directions performed on right stance foot: A) Anterior, B) Posteromedial, C) Posterolateral

2.5 Data Analysis

After data collection was completed, the 5 markers on the foot and ankle (dorsal aspect of first toe, dorsal aspect of second metatarsal head, lateral malleolus, medial malleolus, and heel) of each foot were labeled for each SEBT trial in Vicon Nexus software. Event markers indicating the frames during which toe off and toe touch at maximum reach (Figure 4) occurred were manually labeled in Vicon. Toe off was defined as the sample during which the subject’s reaching foot was completely off the force plate and movement was initiated. Toe touch was the sample during which the subject’s reaching toe first made contact with the floor. Velocity and position data for the 1st toe marker on the reaching foot were used to determine the frame during which these events occurred.

Due to missing markers or problems with the data collection software some trials could not be processed, leaving a total of 2390 trials used for the analysis. Custom MATLAB (MathWorks, Natick, MA) scripts were used to calculate reach distance and TtC. These scripts are presented in Appendix A.
2.5.1 Reach Distance

Reach distance was determined by calculating the distance from the big toe marker of the stance foot to the big toe marker of the reaching foot during the toe touch frame (Figure 4B). Reach distances were normalized to leg length. Leg length was determined by finding the average distance between the anterior superior iliac spine marker and the lateral malleolus markers in Vicon (Plisky 2006).

2.5.2 Time-to-Contact

The markers on the big toe, lateral malleolus, medial malleolus, and heel of each foot were used to identify the base of support (Figure 5). The foot was aligned with the global y-axis and the perimeter of the base of support was formed by connecting the 1st toe to the medial malleolus, the medial malleolus to the heel, and the heel to the lateral malleolus with straight lines. The anterior and lateral borders of the base of support were drawn parallel to the global x- and y-axes, respectively (Figure 5).
TtC to each of the 5 base of support boundaries was calculated for each sample between toe off and toe touch at maximum reach using previously developed equations (Appendix B; Slobounov 1997). The TtC for a sample was the minimum real and positive TtC for that sample as this represents the TtC to the first boundary the CoP would contact. Due to the noisiness of the raw TtC data (Figure 6), to assess changes in TtC during the task, TtC was averaged over 5 epochs, each equal to one-fifth of the reach time (toe off to toe touch at maximum reach; Figure 7).
Figure 6: Raw TtC data for a single trial compared to average TtC over each epoch

Figure 7: Epoch breakdown from toe off to toe touch
2.5.3 Statistical Analysis

To determine how an individual adjusts their postural control during the SEBT, this research investigated differences in TtC between epochs. In addition, the SEBT challenges an individual separately on each stance leg and in multiple directions; therefore, each stance leg and direction combination can be thought of as a separate “task.” Consequently, differences in TtC between side and direction are also assessed. Finally, the three mouthguard conditions also provided a possible source of difference in postural control in this study.

To evaluate these potential differences in TtC during the SEBT, an unbalanced mixed effects analysis of variance (ANOVA) was used including subject, condition, epoch, stance leg side, reach direction, epoch*side and epoch*direction interactions. TtC was not significantly different by mouthguard condition (p=0.2733) and not a main outcome of this work.

Therefore, the data were collapsed across all mouthguard conditions and an unbalanced mixed effects ANOVA was used including subject, epoch, side, direction as main effects and epoch*side and epoch*direction interactions. Post-hoc Tukey’s HSD comparisons (α=0.05) were subsequently used to determine differences between individual epochs. In addition, both a Pearson and Spearman correlation analysis were used to compare the average TtC during Epoch 5 of each subject in each of the three reach directions to the average normalized reach distance of each subject in each of the three reach directions. Both types of correlation analysis were used because the Pearson product-moment correlation coefficient is the measure of the linear dependence between two variables and requires normally-distributed variables, while the Spearman’s rank correlation coefficient does not require a linear relationship between two variables or normal distributions. Only the average TtC during Epoch 5 was used in this analysis.
because this is the epoch during which toe touch occurs. All statistical analyses were conducted utilizing custom MATLAB scripts.

CHAPTER 3 RESULTS

3.1 TtC Analysis of Postural Control

3.1.1 Changes in Postural Control

The results of the ANOVA yielded epoch as a significant main effect (p<0.001). The post-hoc analysis revealed that each epoch was significantly different from the other four epochs (p=0.001). The marginal means between consecutive epochs and the 99% confidence intervals are listed in Table 2. A plot depicting the average TtC and standard error for each epoch can be seen in Figure 8.

<table>
<thead>
<tr>
<th>Epoch Comparison</th>
<th>Mean Difference (ms)</th>
<th>99% Confidence Intervals</th>
</tr>
</thead>
<tbody>
<tr>
<td>1→2</td>
<td>-0.0047</td>
<td>(-0.0004, -0.0091)</td>
</tr>
<tr>
<td>2→3</td>
<td>0.0114</td>
<td>(0.0157, 0.0071)</td>
</tr>
<tr>
<td>3→4</td>
<td>0.0201</td>
<td>(0.0244, 0.0158)</td>
</tr>
<tr>
<td>4→5</td>
<td>0.0237</td>
<td>(0.0281, 0.0194)</td>
</tr>
</tbody>
</table>
Figure 8: Average TtC with standard error bars at each epoch from toe off to toe touch at maximum reach during the SEBT

3.1.2 Task Dependency

Neither stance leg side (p=0.578) or direction (p=0.601) was a significant main effect for TtC.

3.2 Correlation between Time-to-Contact and Reach Distance

Both the Pearson and Spearman correlations found a significant weak correlation between average Epoch 5 TtC in the anterior direction and average anterior reach. The Pearson and Spearman correlation coefficients from the two tests were within thousandths of each other; therefore, because it is known that the Pearson tests the linear relationship, the Pearson linear correlation coefficients are reported (Table 3).
Table 3: Pearson Correlation Coefficients and P-Values for Average Epoch 5 TtC and Average Reach Distance in Each Direction

<table>
<thead>
<tr>
<th>Direction</th>
<th>Correlation Coefficient</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anterior</td>
<td>-0.3169</td>
<td>0.0319</td>
</tr>
<tr>
<td>Posteromedial</td>
<td>-0.1436</td>
<td>0.3425</td>
</tr>
<tr>
<td>Posterolateral</td>
<td>-0.0325</td>
<td>0.8300</td>
</tr>
</tbody>
</table>

* indicates statistically significant

CHAPTER 4 DISCUSSION

4.1 TtC Analysis of Postural Control

4.1.1 Changes in Postural Control

The significant difference in TtC between epochs indicates that individuals modulate their postural control during a dynamic balance test. The initial decrease in TtC from Epoch 1 to Epoch 2 occurs early in the reach while the reaching foot is still relatively close to the body. At this time, there is decreased demand of the postural control system because the threat of the individual exceeding their limits of stability is relatively small. Thus, the lower TtC observed may correspond to decrease postural control demands at this point in the test. Previous studies compared differences in postural control between ballet dancers and non-dancers during quiet standing. The dancers exhibited greater variability, lower mathematical stability and increased noisiness in the COP time series (Schmit 2005) and lower Time-to-Boundary (calculated as instantaneous distance to the base of support divided by instantaneous velocity) (Fidler 2005). These results suggest that due to their superior balance training, ballet dancers can allow more flexibility in their posture during less demanding tasks. Fidler et al. theorized that the amount of variability in postural control an individual exhibits is related to the difficulty of the task, such
that when the neuromuscular system can adeptly meet the demands of the task, the individual does not need to strictly maintain their posture (Fidler 2005).

TtC progressively increases over the next three epochs, as the reaching limb approaches the point of toe touch. The challenge to the postural control system increases during this period of the test, both due to the requirement to touch the toe at a single point with minimal force and because the reaching foot is being extended further from the base of support. Therefore, the longer TtC observed suggests individuals may be exhibiting greater postural control to maintain stability. Haddad et al. observed a similar TtC pattern for the precision fitting activity, noting that TtC was longer in the later epochs of the test (Haddad 2010). Furthermore, longer TtC was observed throughout the trials that required the subjects to fit the block through the smaller hole. These results suggest that healthy individuals incrementally increase their postural control as the difficulty and precision demands of the activity increase.

4.1.2 Task Dependency

Postural control, as measured by TtC, did not demonstrate any task dependency on the stance leg or on the direction of the reach (Section 3.1.2). Previous literature has reported side-to-side asymmetry in reach distance as predictive of lower extremity injury (Plisky 2006) and a method for differentiating between patients with and without chronic ankle instability (Olmsted 2002). Taking into account that the population analyzed for this work consisted of healthy, active subjects, it is not surprising that no side-to-side asymmetry was observed for TtC. Future studies should evaluate TtC during the SEBT for individuals with a lower extremity pathology, such as chronic ankle instability, to determine the efficacy of TtC as a discriminative measure for identifying individuals with postural control deficits.
It is likely that differences in TtC between reach directions were not observed because of the method used to calculate TtC. Although the direction in which the CoP is displaced may depend on the direction the task is being performed, the TtC for each sample was determined by the minimum time to any of the five stability boundaries. Therefore, the TtC calculation likely minimizes the importance of reach direction in analyzing postural control during the SEBT. The clinical implication of this is finding is that it may be possible to simplify the SEBT to a single reach direction using TtC analysis. Because the SEBT has been shown to be an effective injury risk screening tool (Plisky 2006), by reducing the test to one direction, data collection time could be significantly reduced when testing large populations, like an athletic team, during a single testing session.

4.2 Correlation between Time-to-Contact and Reach Distance

The very weak negative correlation between normalized anterior reach distance and Epoch 5 TtC during anterior reach may suggest there could be a relationship between the distance an individual can reach and the level of postural control they exert. A negative correlation would indicate that an individual maintaining a higher level of postural control, corresponding to a longer TtC, displays decreased functional performance, measured by reach distance. This could potentially suggest that individuals with better postural stability exhibit better functional performance because they are capable of maintaining their balance with decreased input from their postural control system. This theory would be consistent with the findings of previously mentioned postural control studies of ballet dancers, who are capable of maintaining lower levels of postural control while performing the same task as individuals with less balance training (Schmitt 2005). Conversely, individuals with poor postural stability may
exhibit a lower level of functional performance because there are high demands on their postural control system to meet the demands of the task. However, due to the very weak correlation reported in this work, further research is necessary to investigate this theory. A study that evaluated both TtC and reach distance measures in populations with balance training, such as ballet dancers, during the SEBT may offer a better understanding of the relationship between functional performance and postural control.

It is important to note that although no differences were observed between directions for TtC alone, a correlation was observed between TtC and reach distance only for the anterior reach. Reach distance is affected by the direction of the reach partly because each direction involves a different muscle activation pattern (Earl 2001). Therefore, reach distance could be affected by the individual strength of each muscle necessary to complete a reach in a specific direction. Furthermore, the anterior reach is a more familiar movement, because it is to some extent similar to taking a step forward, compared to the posterior (posterolateral and posteromedial) reaches. The unfamiliarity of the movement required by the posterior reaches may cause greater variability in reach distances between subjects.

Alternatively, it may be possible to infer from the very weak correlation that no clinically meaningful correlation exists between TtC and reach distance. All of the trials analyzed in this study were successfully completed reaches, meaning that the individual’s postural control system was capable of controlling the location of the COP within the base of support throughout the task. Therefore, an individual’s reach distance may have been limited by an aspect independent of their postural control system, such as their leg and core muscle strength or their lower extremity joint flexibility.
CHAPTER 5  CONCLUSION

5.1  Limitations and Suggestions for Future Work

5.1.1  Subject Population

The subject population examined in this study consisted of healthy, recreational athletes. While this population can provide insights into how healthy individuals modulate their postural control, we cannot establish what thresholds of TtC are appropriate or allowable during a dynamic activity. To gain a fuller understanding of how TtC relates to postural control, comparisons of TtC between individuals with pathologies associated with postural control deficits and individuals with elite levels of balance, such as dancers, ice skaters, or gymnasts, should be evaluated during functional dynamic activities.

5.1.2  Traditional CoP Measures

This work does not compare TtC to traditional CoP measures; however, it may be possible to average measures such as CoP excursion or velocity over epochs within a trial to reveal changes in levels of postural control. Further research is necessary to determine which measures may be most sensitive to postural control changes within a task. Additionally, normalized maximum reach distances could be compared to average values of traditional measures during epoch 5 to investigate the relationship between functional performance and postural control. Similarly, reach distance could be compared to single averaged traditional measures over the entire test. Differences between the correlation of reach distance and the epoch 5 measure and the correlation of reach distance and the global measure may indicate the efficacy of breaking down a dynamic task into epochs to evaluate postural control.
5.1.3 Flexibility and Strength

It is unclear as to which aspects of postural control TtC is capturing during the SEBT. TtC provides information about how an individual controls their posture within their limits of stability. However, balance activities like the SEBT challenge not only an individual’s neuromuscular feedback system, but also their strength and joint flexibility, particularly at the ankle. In individuals with impaired ankle mobility, decreased dorsiflexion range of motion has been suggested to affect reach distance during the SEBT (Olmsted 2002; Hoch 2012). To determine how an individual’s flexibility may relate to an individual’s postural control response, dorsiflexion and TtC measures should be compared during the SEBT.

Additionally, correlation of TtC with EMG measures of leg and core muscle activation during the SEBT may clarify the relationship between strength and neuromuscular control. Core strength has been shown to be related to SEBT performance (Tsukagoshi 2011). Furthermore, previous work has used EMG to demonstrate differences in muscle activation between reach directions during the SEBT, suggesting that individuals use different muscle control patterns to accomplish the task based on reach direction (Earl 2001). However, upper extremity movement and heel contact with floor were not constrained in that study. Additional compensation strategies could be investigated using both EMG measures as well as hip and knee angles during the SEBT. Relationships between these measures and TtC during SEBT trials may reveal how individuals control their posture to maintain their CoP within their limits of stability.

Together, these measures of joint range of motion and strength could be used to better understand the effects of flexibility, strength, and neuromuscular control on postural control during dynamic tasks.
5.2 Summary

This research is one of the first to demonstrate that healthy individuals modulate their postural control during dynamic lower extremity tasks. The observed lower TtC while the reaching foot is close to the body and increase in TtC as the reaching limb extends further from the base of support promote the theory that the difficulty of a task influences the level of postural control an individual must exert to maintain stability. In addition, because there were no differences in TtC between reach directions, this may allow for a single reach direction to be used to assess postural control. Therefore, TtC may be an efficient clinical measure for using the SEBT as a screening tool for postural control deficits and increased injury risk when evaluating large populations in a single testing session, such as pre-season screening for an athletic team. Finally, the weak negative correlation between average anterior normalized reach and average Epoch 5 TtC should be explored further, particularly in populations with superior balance training, such as gymnasts and dancers, to investigate if an inverse relationship may exist between functional performance and postural control. Future work is needed to evaluate the relationship between neuromuscular control measures, such as TtC, and other factors impacting functional performance during the SEBT, including joint flexibility and strength. Finally, in addition to these factors, future research should investigate the individual contributions of APA and APR strategies to overall postural control and the TtC measure.
APPENDIX A: MATLAB SCRIPTS

Pull Raw Data from Vicon

```matlab
%SEBT_PullData
%Modified from LevelBelt_PullData.m
%Sarah Schloemer
%Ohio State University
%8/25/2010
%Modified for CoP Data 10/14/2010

% Pulls marker data for all feet markers and CHIN, BSKLL.
% Calculates distance between LBIGT and RBIGT markers at foot strike event.
% Assumes one foot strike per trial.
% Also pulls CoP data from Force Plate 3. Assumes subject is standing on
% only Force Plate 3.

% Pull original FP data, steps to find valid frames for CoP measures
%---------------------

clear

%% Initialize parameters and PECS server
load all_labels;

p = path;
semicolon = findstr(p,';');
STORE_DIRECTORY = 'M:\Ajit Lab\FBPCT Matlab code\Mouthguard Data\SEBT_CoP_04032012';

% Store current directory and change directory to where all ADLpay data
% is stored
original_directory = pwd;
if ~exist(STORE_DIRECTORY,'dir'),
mkdir(STORE_DIRECTORY);
end
cd(STORE_DIRECTORY);

all_Labels = {'LBIGT', 'LANK', 'LHEE', 'LTOE', 'LMMA', ...
'RBIGT', 'RANK', 'RHEE', 'RTOE', 'RMMA', ...
'CHIN', 'BSKLL'};

LBIGT = 1;
LANK = 2;
LHEE = 3;
LTOE = 4;
LMMA = 5;

RBIGT = 6;
```
RANK = 7;
RHEE = 8;
RTOE = 9;
RMMA = 10;

CHIN = 11;
BSKLL = 12;

% Get hold of PECS (returns a handle to an ActiveX object)
hPECS = actxserver('PECS.Document');

% Open the trial (returns a handle to an ActiveX object)
hTrial = get(hPECS,'Trial');

% Open the processor
hProcessor = get(hPECS,'Processor');

% Getting trial information for naming the file later
hEclipseNode = get(hTrial,'EclipseNode');
TrialName = get(hEclipseNode,'Title');
Description = get(hTrial,'Description');
Notes = get(hTrial,'Notes');
TrialType = get(hTrial,'Type');
release(hEclipseNode);

trial_type = DYNAMIC; % Allows PECSPullData to look for gaps

PECSPullData; % Pulls all trajectory data

%% Pull original force plate data
nforceplates = get(hTrial,'ForcePlateCount');
atovratio = zeros(nforceplates,2);
samplenums = atovratio;
samplerates = zeros(nforceplates);
cop_data = cell(nforceplates,2);
force_data = cell(nforceplates,2);
for ctr=1:nforceplates,
    hForcePlate = get(hTrial,'ForcePlate',ctr-1);
samplerates(ctr) = get(hForcePlate,'SampleRate');
hRatio = get(hForcePlate,'AnalogToVideoRatio');
atovratio(ctr,:) = [get(hRatio,'Numerator'),get(hRatio,'Denominator')];
release(hRatio);
samplenums(ctr,:) = [get(hForcePlate,'FirstSampleNum'),get(hForcePlate,'LastSampleNum')];
cop_data{ctr} = get(hForcePlate,'GetCenterOfPressures',samplenums(ctr,1),samplenums(ctr,2));
    force_data{ctr} = get(hForcePlate,'GetForces',samplenums(ctr,1),samplenums(ctr,2));
end
for ctr=1:nforceplates,
    fdx = force_data{ctr};
fd(ctr,:) = fdx(3,:);
end
mfd = max(fd,[],2);
[dummy,whichplate] = max(mfd);
raw_CoP_analog = cop_data{whichplate}; % The center of pressure data for
    the force plate with the largest peak force on it through the whole trial
t_analog = ((samplenums(whichplate,1):samplenums(whichplate,2)));
    % The
time (in samples) associated with each sample in the CoP data
rate_multiplier = atovratio(whichplate, 1)/atovratio(whichplate, 2);

%% calc reach distance
hEventStore = get(hTrial,'EventStore');
nEvents = get(hEventStore,'EventCount');
nContexts = get(hEventStore,'EventContextCount');
for ctr=1:nEvents,
    hEvent = get(hEventStore,'Event',ctr-1);
    hContext = get(hEvent,'Context');
    eventdesc{ctr} = get(hEvent,'Description');
    contextlabel{ctr} = get(hContext,'Label');
    eventtime(ctr) = get(hEvent,'Time');
    release(hContext);
    release(hEvent);
end
release(hEventStore);

videorate = get(hTrial,'VideoRate');
eventtime = int32(floor(eventtime * videorate + 1)); % convert from time
to frame number
contexts = char(contextlabel);

% get frame of tap reach distance
reach_idx = find(strcmp(eventdesc,'Foot Strike'));
if isempty(reach_idx)
    reach_idx = find(strcmp(eventdesc,'The instant the heel strikes the
    ground'));
end
reach_frame = eventtime(reach_idx);

% get position data of big toes at tap reach frame
reach_LBIGTxy = data(1:2, reach_frame, labelidx(LBIGT));
reach_RBIGTxy = data(1:2, reach_frame, labelidx(RBIGT));

% calculate tap reach distance
reach_x = reach_LBIGTxy(1) - reach_RBIGTxy(1);
reach_y = reach_LBIGTxy(2) - reach_RBIGTxy(2);
tap_reach_distance = sqrt((reach_x)^2 + (reach_y)^2);

% find stance foot of trial
if isempty(find(strcmp('Left', contextlabel)))
    stancefoot='L';
else if isempty(find(strcmp('Right', contextlabel)))
    stancefoot='R';
else
stancefoot='no stance foot found';
errstr = sprintf('No stance foot found for %s_%s',subjectname,TrialName);
errordlg(errstr,'Stance Foot Error');
end

% determine direction of trial
if stancefoot == 'L'
    if data(1, reach_frame, labelidx(RBIGT)) > 0 && data(2, reach_frame, labelidx(RBIGT)) > -500
        My_Description = 'Lposl';
    elseif data(1, reach_frame, labelidx(RBIGT)) < 0 && data(2, reach_frame, labelidx(RBIGT)) > -500
        My_Description = 'Lposm';
    elseif data(1, reach_frame, labelidx(RBIGT)) > 0 && data(2, reach_frame, labelidx(RBIGT)) < -500
        My_Description = 'Lant';
    else
        My_Description = 'indt';
    end
else
    if stancefoot == 'R'
        if data(1, reach_frame, labelidx(LBIGT)) > 0 && data(2, reach_frame, labelidx(LBIGT)) > -500
            My_Description = 'Rposl';
        elseif data(1, reach_frame, labelidx(LBIGT)) < 0 && data(2, reach_frame, labelidx(LBIGT)) > -500
            My_Description = 'Rposm';
        elseif data(1, reach_frame, labelidx(LBIGT)) > 0 && data(2, reach_frame, labelidx(LBIGT)) < -500
            My_Description = 'Rant';
        else
            My_Description = 'indt';
        end
    else
        if stancefoot == 'no stance foot found'
            My_Description = 'NSF';
        end
    end
end

% Find first & last frames for CoP

% get valid frames of LBIGT and RIBGT markers
firstValidBIGT = max([firstValid(labelidx(LBIGT)), firstValid(labelidx(RBIGT))]);
lastValidBIGT = min([lastValid(labelidx(LBIGT)), lastValid(labelidx(RBIGT))]);

% find valid frames for CoP measures
COP_first_idx = find(strcmp(eventdesc, 'Foot Off'));
if isempty(COP_first_idx)
    COP_first_idx = find(strcmp(eventdesc, 'The instant the toe leaves the ground'));
end
if length(COP_first_idx) == 1
    COP_first_frame = eventtime(COP_first_idx);
elseif isempty(COP_first_idx)
    COP_first_frame = firstValidBIGT;
else
    COP_first_frame = 'First COP Frame Could Not Be Determined';
    errstr = sprintf('First COP Frame not determined for %s_%s', subjectname, TrialName);
    errordlg(errstr, 'First COP Frame Error');
end

COP_last_idx = find(strcmp(eventdesc, 'Event'));
if isempty(COP_last_idx)
    COP_last_idx = find(strcmp(eventdesc, 'A general (unspecified) event'));
end
if COP_last_idx ~= 0
    eventframe = eventtime(COP_last_idx);
    if length(eventframe) == 1
        COP_last_frame = eventtime(COP_last_idx);
    elseif length(eventframe) == 3
        eventorder = sort(eventframe);
        COP_last_frame = eventorder(2);
    else
        COP_last_frame = 'Last COP Frame Could Not Be Determined';
        errstr = sprintf('Last COP Frame not determined for %s_%s', subjectname, TrialName);
        errordlg(errstr, 'Last COP Frame Error');
    end
    elseif isempty(COP_last_idx)
        COP_last_frame = lastValidBIGT;
    else
        COP_last_frame = 'Last COP Frame Could Not Be Determined';
        errstr = sprintf('Last COP Frame not determined for %s_%s', subjectname, TrialName);
        errordlg(errstr, 'Last COP Frame Error');
    end

% Convert frame numbers to sample numbers
tap_sample = reach_frame*rate_multiplier;
first_CoP_sample = COP_first_frame*rate_multiplier;
last_CoP_sample = COP_last_frame*rate_multiplier;
epoch_length = (tap_sample - first_CoP_sample)*.2; % number of frames per epoch

% Find instantaneous position, velocity and acceleration

% filter FP data
unfiltered_CoP = raw_CoP_analog;
cutoff_frequency = [30];
butter_frequency = (cutoff_frequency)/((videorate*rate_multiplier)/2);
[b,a]=butter(4,butter_frequency,'low');
CoP_analog = filtfilt(b,a,unfiltered_CoP');

% get position data over all frames
COP_x_position = CoP_analog(1, :);
COP_y_position = CoP_analog(2, :);
% get velocity data over all frames
% firstvasample = t_analog(4);
% lastvasample = t_analog(length(t_analog)) - 1;
firstvasample = 3;
lastvasample = length(t_analog) - 2;

for currentsample = firstvasample:lastvasample
    COP_x_velocity(currentsample) = (-COP_x_position(currentsample + 2) + 8*COP_x_position(currentsample + 1) - 8*COP_x_position(currentsample - 1) + COP_x_position(currentsample - 2))/(12*(1/(videorate*rate_multiplier)));
    COP_y_velocity(currentsample) = (-COP_y_position(currentsample + 2) + 8*COP_y_position(currentsample + 1) - 8*COP_y_position(currentsample - 1) + COP_y_position(currentsample - 2))/(12*(1/(videorate*rate_multiplier)));
end

% get acceleration data over all frames
for currentsample = firstvasample:lastvasample
    COP_x_acceleration(currentsample) = (-COP_x_position(currentsample + 2) + 16*COP_x_position(currentsample + 1) - 30*COP_x_position(currentsample) + 16*COP_x_position(currentsample - 1) - COP_x_position(currentsample - 2))/(12*((1/(videorate*rate_multiplier))^2));
    COP_y_acceleration(currentsample) = (-COP_y_position(currentsample + 2) + 16*COP_y_position(currentsample + 1) - 30*COP_y_position(currentsample) + 16*COP_y_position(currentsample - 1) - COP_y_position(currentsample - 2))/(12*((1/(videorate*rate_multiplier))^2));
end

%% Calculate Time to Contact
% Find average positions of feet markers
firstvalid_Lfoot=max([firstValid(labelidx(LBIGT)), firstValid(labelidx(LANK)), firstValid(labelidx(LMMA)), firstValid(labelidx(LHEE))]);
lastvalid_Lfoot=min([lastValid(labelidx(LBIGT)), lastValid(labelidx(LANK)), lastValid(labelidx(LMMA)), lastValid(labelidx(LHEE))]);

firstvalid_Rfoot=max([firstValid(labelidx(RBIGT)), firstValid(labelidx(RANK)), firstValid(labelidx(RMMA)), firstValid(labelidx(RHEE))]);
lastvalid_Rfoot=min([lastValid(labelidx(RBIGT)), lastValid(labelidx(RANK)), lastValid(labelidx(RMMA)), lastValid(labelidx(RHEE))]);

if stancefoot == 'L'
    data_LBIGT = data(:, firstvalid_Lfoot:lastvalid_Lfoot, labelidx(LBIGT));
    LBIGTNaNIdx = find(isnan(data_LBIGT(1,:)));
    data_LBIGT(:, LBIGTNaNIdx) = [];
    avg_x_LBIGT = mean(data_LBIGT(1,:));
end
avg_y_LBIGT = mean(data_LBIGT(2, :));

data_LANK = data(:, firstvalid_Lfoot:lastvalid_Lfoot, labelidx(LANK));
LANKNaNidx = find(isnan(data_LANK(1,:)));
data_LANK(:, LANKNaNidx) = [];
avg_x_LANK = mean(data_LANK(1, :));
avg_y_LANK = mean(data_LANK(2, :));

data_LMMA = data(:, firstvalid_Lfoot:lastvalid_Lfoot, labelidx(LMMA));
LMMANaNidx = find(isnan(data_LMMA(1,:)));
data_LMMA(:, LMMANaNidx) = [];
avg_x_LMMA = mean(data_LMMA(1, :));
avg_y_LMMA = mean(data_LMMA(2, :));

data_LHEE = data(:, firstvalid_Lfoot:lastvalid_Lfoot, labelidx(LHEE));
LHEENaNidx = find(isnan(data_LHEE(1,:)));
data_LHEE(:, LHEENaNidx) = [];
avg_x_LHEE = mean(data_LHEE(1, :));
avg_y_LHEE = mean(data_LHEE(2, :));

elseif stancefoot == 'R'
data_RBIGT = data(:, firstvalid_Rfoot:lastvalid_Rfoot, labelidx(RBIGT));
RBIGTNaNidx = find(isnan(data_RBIGT(1,:)));
data_RBIGT(:, RBIGTNaNidx) = [];
avg_x_RBIGT = mean(data_RBIGT(1, :));
avg_y_RBIGT = mean(data_RBIGT(2, :));

data_RANK = data(:, firstvalid_Rfoot:lastvalid_Rfoot, labelidx(RANK));
RANKNaNidx = find(isnan(data_RANK(1,:)));
data_RANK(:, RANKNaNidx) = [];
avg_x_RANK = mean(data_RANK(1, :));
avg_y_RANK = mean(data_RANK(2, :));

data_RMMA = data(:, firstvalid_Rfoot:lastvalid_Rfoot, labelidx(RMMA));
RMMANaNidx = find(isnan(data_RMMA(1,:)));
data_RMMA(:, RMMANaNidx) = [];
avg_x_RMMA = mean(data_RMMA(1, :));
avg_y_RMMA = mean(data_RMMA(2, :));

data_RHEE = data(:, firstvalid_Rfoot:lastvalid_Rfoot, labelidx(RHEE));
RHEENaNidx = find(isnan(data_RHEE(1,:)));
data_RHEE(:, RHEENaNidx) = [];
avg_x_RHEE = mean(data_RHEE(1, :));
avg_y_RHEE = mean(data_RHEE(2, :));
% elseif stancefoot == 'no stance foot found'
end
ctr=1;
if isempty(COP_last_idx)
    TtC_sample_alpha = find(t_analog==first_CoP_sample);
    TtC_sample_omega = find(t_analog==(last_CoP_sample-3));
else
    TtC_sample_alpha = find(t_analog==first_CoP_sample);
    TtC_sample_omega = find(t_analog==last_CoP_sample);
end

%% Save File
filename = [subjectname ' ' TrialName ' ' TrialType '.mat'];
invoke(hProcessor,'Log',sprintf('Wrote %s in %s',filename,STORE_DIRECTORY),1);

%% -------------------End automation for different segments here-------
% Release everything
release( hProcessor );
release( hTrial );
release( hPECS );
clear
ctx
release
EventNode
Event
EventStore
PECS
Processor
Subject
Trajectory
Trial
save(filename);
cd(original_directory);

---
Calculate TtC and Traditional CoP Measures

%% SEBT_Traditional_Measures.m
% Sarah Schloemer
% Ohio State University
% 3/28/2012

% Calculates TtC and determines which boundary is contacted at each sample
% in the trial. % Calculates traditional measures of postural stability for SEBT trials
% from mouthguard study. Both global and epoch measurements are calculated.
% Prints all outcome measures to spreadsheet.

% -------------------
clc; clear;
directory_name = uigetdir('','Pick directory with all the .mat data files');
% directory_name = 'M:\Ajit Lab\FBPCT Matlab code\Mouthguard 
Data\SEBT_CoP';
clc
cd(directory_name);
files = dir('*'.mat');
nfiles = length(files);
fid = fopen(sprintf('SEBT_%f.tsv',datenum(clock)),'w');
saveworkspacevars;
for counter=1:nfiles-1
clearvars-exceptdirectory_namefilesnfilesfidcounter
fprintf('%d of %d 
',counter,nfiles);
filename = files(counter).name;
load(filename);
loadworkspacevars;
%% Calculate Time to Contact

h = 1;
% time to contact 5 stability boundaries
if strcmp(stancefoot, 'no stance foot found') == 0
for thissample = TtC_sample_alpha:TtC_sample_omega
if stancefoot == 'R'
% stability boundary 1
    ml = 0;
    yboundary1 = avg_y_RBIGT;
    xboundary1 = 0;
    A1 = (COP_y_acceleration(thissample) - (ml * 

COP_x_acceleration(thissample))/2;
    B1 = COP_y_velocity(thissample) - (ml * 

COP_x_velocity(thissample);
    C1 = COP_y_position(thissample) - yboundary1 - ml *

(COP_x_position(thissample) - xboundary1);
    TtC_1_plus = (-B1 + sqrt(B1^2 - 4*A1*C1))/(2*A1);
    TtC_1_minus = (-B1 - sqrt(B1^2 - 4*A1*C1))/(2*A1);

% stability boundary 2
    A2 = COP_x_acceleration(thissample)/2;
    B2 = COP_x_velocity(thissample);
    C2 = COP_x_position(thissample) + avg_x_RANK;
    TtC_2_plus = (-B2 + sqrt(B2^2 - 4*A2*C2))/(2*A2);
    TtC_2_minus = (-B2 - sqrt(B2^2 - 4*A2*C2))/(2*A2);

% stability boundary 3
    m3 = (avg_y_RANK - avg_y_RHEE)/(avg_x_RANK - avg_x_RHEE);
    yboundary3 = avg_y_RANK;
    xboundary3 = avg_x_RANK;
    A3 = (COP_y_acceleration(thissample) - (m3 *

COP_x_acceleration(thissample))/2;
    B3 = COP_y_velocity(thissample) - (m3 *

COP_x_velocity(thissample);
    C3 = COP_y_position(thissample) - yboundary3 - m3 *

(COP_x_position(thissample) - xboundary3);
    TtC_3_plus = (-B3 + sqrt(B3^2 - 4*A3*C3))/(2*A3);
    TtC_3_minus = (-B3 - sqrt(B3^2 - 4*A3*C3))/(2*A3);

% stability boundary 4
    m4 = (avg_y_RMMA - avg_y_RHEE)/(avg_x_RMMA - avg_x_RHEE);
    yboundary4 = avg_y_RHEE;
    xboundary4 = avg_x_RHEE;
A4 = (COP_y_acceleration(thissample) - (m4 * COP_x_acceleration(thissample))) / 2;
B4 = COP_y_velocity(thissample) - (m4 * COP_x_velocity(thissample));
C4 = COP_y_position(thissample) - y_boundary4 - m4 * (COP_x_position(thissample) - x_boundary4);
TtC_4_plus = (-B4 + sqrt(B4^2 - 4*A4*C4)) / (2*A4);
TtC_4_minus = (-B4 - sqrt(B4^2 - 4*A4*C4)) / (2*A4);

% stability boundary 5
m5 = (avg_y_RBIGT - avg_y_RMMA) / (avg_x_RBIGT - avg_x_RMMA);
y_boundary5 = avg_y_RMMA;
x_boundary5 = avg_x_RMMA;
A5 = (COP_y_acceleration(thissample) - (m5 * COP_x_acceleration(thissample))) / 2;
B5 = COP_y_velocity(thissample) - (m5 * COP_x_velocity(thissample));
C5 = COP_y_position(thissample) - y_boundary5 - m5 * (COP_x_position(thissample) - x_boundary5);
TtC_5_plus = (-B5 + sqrt(B5^2 - 4*A5*C5)) / (2*A5);
TtC_5_minus = (-B5 - sqrt(B5^2 - 4*A5*C5)) / (2*A5);

% Compare TtC's - choose smallest positive
Possible_TtCs = [TtC_1_plus, TtC_1_minus, TtC_2_plus, TtC_2_minus, TtC_3_plus, TtC_3_minus, TtC_4_plus, TtC_4_minus, TtC_5_plus, TtC_5_minus];
for i = 1:length(Possible_TtCs)
    Real_TtCs_idx(i) = isreal(Possible_TtCs(i));
    Real_TtCs(i) = Possible_TtCs(i) * Real_TtCs_idx(i);
end
Positive_TtCs = Real_TtCs(find(Real_TtCs > 0));
TtC(h) = min(Positive_TtCs);
location = find(Possible_TtCs == TtC(h));
if location == 1 || location == 3 || location == 5 || location == 7 || location == 9
    boundary(h) = (location + 1) / 2;
elseif location == 2 || location == 4 || location == 6 || location == 8
    location == 10
    boundary(h) = location / 2;
end
h = h + 1;

elseif stancefoot == 'L'
% stability boundary 1
m1 = 0;
y_boundary1 = avg_y_LBIGT;
x_boundary1 = 0;
A1 = (COP_y_acceleration(thissample) - (m1 * COP_x_acceleration(thissample))) / 2;
B1 = COP_y_velocity(thissample) - (m1 * COP_x_velocity(thissample));
C1 = COP_y_position(thissample) - y_boundary1 - m1 * (COP_x_position(thissample) - x_boundary1);
TtC_1_plus = (-B1 + sqrt(B1^2 - 4*A1*C1)) / (2*A1);
TtC_1_minus = (-B1 - sqrt(B1^2 - 4*A1*C1)) / (2*A1);

% stability boundary 2
A2 = COP_x_acceleration(thissample)/2;
B2 = COP_x_velocity(thissample);
C2 = COP_x_position(thissample) + avg_x_LANK;
TtC_2_plus = (-B2 + sqrt(B2^2 - 4*A2*C2))/(2*A2);
TtC_2_minus = (-B2 - sqrt(B2^2 - 4*A2*C2))/(2*A2);

% stability boundary 3
m3 = (avg_y_LANK - avg_y_LHEE)/(avg_x_LANK - avg_x_LHEE);
y_boundary3 = avg_y_LANK;
x_boundary3 = avg_x_LANK;
A3 = (COP_y_acceleration(thissample) - (m3 * COP_x_acceleration(thissample)))/2;
B3 = COP_y_velocity(thissample) - (m3 * COP_x_velocity(thissample));
C3 = COP_y_position(thissample) - y_boundary3 - m3 * (COP_x_position(thissample) - x_boundary3);

% stability boundary 4
m4 = (avg_y_LMMA - avg_y_LHEE)/(avg_x_LMMA - avg_x_LHEE);
y_boundary4 = avg_y_LHEE;
x_boundary4 = avg_x_LHEE;
A4 = (COP_y_acceleration(thissample) - (m4 * COP_x_acceleration(thissample)))/2;
B4 = COP_y_velocity(thissample) - (m4 * COP_x_velocity(thissample));
C4 = COP_y_position(thissample) - y_boundary4 - m4 * (COP_x_position(thissample) - x_boundary4);

% stability boundary 5
m5 = (avg_y_LBIGT - avg_y_LMMA)/(avg_x_LBIGT - avg_x_LMMA);
y_boundary5 = avg_y_LMMA;
x_boundary5 = avg_x_LMMA;
A5 = (COP_y_acceleration(thissample) - (m5 * COP_x_acceleration(thissample)))/2;
B5 = COP_y_velocity(thissample) - (m5 * COP_x_velocity(thissample));
C5 = COP_y_position(thissample) - y_boundary5 - m5 * (COP_x_position(thissample) - x_boundary5);

%Compare TtC's - choose smallest positive
Possible_TtCs = [TtC_1_plus, TtC_1_minus, TtC_2_plus, TtC_2_minus, TtC_3_plus, TtC_3_minus, TtC_4_plus, TtC_4_minus, TtC_5_plus, TtC_5_minus];
for i = 1:length(Possible_TtCs)
    Real_TtCs_idx(i) = isreal(Possible_TtCs(i));
    Real_TtCs(i) = Possible_TtCs(i)*Real_TtCs_idx(i);
end
Possible_TtCs = Real_TtCs(find(Real_TtCs > 0));
TtC(h) = min(Possible_TtCs);
location = find(Possible_TtCs == TtC(h));
if location == 1 || location == 3 || location == 5 || location == 7 || location == 9
boundary(h) = (location + 1)/2;
elseif location == 2 || location == 4 || location == 6 || location == 8 || location == 10
boundary(h) = location/2;
end
h=h+1;
end
end

num_of_epochs = floor((double(TtC_sample_omega - TtC_sample_alpha)+1)/double(epoch_length)); %finds number of epochs for trial

% average TtC over epochs
for ctr = 1:num_of_epochs
    TtC_over_epoch(ctr) = mean(TtC(floor(1 + (ctr-1)*epoch_length):floor(ctr*epoch_length)));
end
end

%% COP Excursion
% Global
avg_CoP_x = mean(COP_x_position(TtC_sample_alpha:TtC_sample_omega));
avg_CoP_y = mean(COP_y_position(TtC_sample_alpha:TtC_sample_omega));

% Take absolute value of difference between average COP position and instantaneous COP position --> get all positive values
i=1;
for currentsample = TtC_sample_alpha:TtC_sample_omega
    difference_from_avg_x(i) = abs(COP_x_position(currentsample) - avg_CoP_x);
    difference_from_avg_y(i) = abs(COP_y_position(currentsample) - avg_CoP_y);
    i=i+1;
end
mean_COP_Exc_x = mean(difference_from_avg_x);
mean_COP_Exc_y = mean(difference_from_avg_y);
max_COP_Exc_x = max(difference_from_avg_x);
max_COP_Exc_y = max(difference_from_avg_y);

% Temporal
for ctr = 1:num_of_epochs
    COP_Exc_x_over_epoch(ctr) = mean(difference_from_avg_x(floor(1 + (ctr-1)*epoch_length):floor(ctr*epoch_length)));
    COP_Exc_y_over_epoch(ctr) = mean(difference_from_avg_y(floor(1 + (ctr-1)*epoch_length):floor(ctr*epoch_length)));
end

%% Standard Deviation of CoP
% Global
% Calculated using equation
% \( N = (\text{last\_CoP\_sample} - \text{first\_CoP\_sample}) + 1; \)
% \( \text{StandDev\_x} = \sqrt{\frac{1}{N} \sum (\text{difference\_from\_avg\_x}(:).^2)}; \)
% \( \text{StandDev\_y} = \sqrt{\frac{1}{N} \sum (\text{difference\_from\_avg\_y}(:).^2)}; \)

% Calculated using MATLAB standard deviation function
SD_x = std(COP_x_position(TtC_sample_alpha:TtC_sample_omega));
SD_y = std(COP_y_position(TtC_sample_alpha:TtC_sample_omega));

% Temporal - Calculated base on MATLAB function
for ctr = 1:num_of_epochs
    StandDev_x_over_epoch(ctr) = mean(std(COP_x_position(floor(TtC_sample_alpha + (ctr-1)*epoch_length):floor(TtC_sample_alpha + (ctr*epoch_length) - 1))));
    StandDev_y_over_epoch(ctr) = mean(std(COP_y_position(floor(TtC_sample_alpha + (ctr-1)*epoch_length):floor(TtC_sample_alpha + (ctr*epoch_length) - 1))));
end

% Total COP Excursion - Global calculation only
current_sum = 0;
for currentsample = TtC_sample_alpha:(TtC_sample_omega-1)
    D = sqrt((COP_x_position(currentsample+1) - COP_x_position(currentsample))^2 + (COP_y_position(currentsample+1) - COP_y_position(currentsample))^2);
    Total_Exc = current_sum + D;
    current_sum = Total_Exc;
end

%% COP Velocity
% Global
avg_CoP_x_velocity = mean(abs(COP_x_velocity(TtC_sample_alpha:TtC_sample_omega)));
avg_CoP_y_velocity = mean(abs(COP_y_velocity(TtC_sample_alpha:TtC_sample_omega)));
max_CoP_x_velocity = max(abs(COP_x_velocity(TtC_sample_alpha:TtC_sample_omega)));
max_CoP_y_velocity = max(abs(COP_y_velocity(TtC_sample_alpha:TtC_sample_omega)));

%% Temporal
for ctr = 1:num_of_epochs
    COP_Vel_x_over_epoch(ctr) = mean(abs(COP_x_velocity(floor(TtC_sample_alpha + (ctr-1)*epoch_length):floor(TtC_sample_alpha + (ctr*epoch_length) - 1))));
    COP_Vel_y_over_epoch(ctr) = mean(abs(COP_y_velocity(floor(TtC_sample_alpha + (ctr-1)*epoch_length):floor(TtC_sample_alpha + (ctr*epoch_length) - 1))));
end

%% COP Area
% Global
min_CoP_x_position_global = min(COP_x_position(TtC_sample_alpha:TtC_sample_omega));
\[\text{min\_COP\_y\_position\_global} = \text{min(COP\_y\_position(TtC\_sample\_alpha:TtC\_sample\_omega))};\]
\[\text{max\_COP\_x\_position\_global} = \text{max(COP\_x\_position(TtC\_sample\_alpha:TtC\_sample\_omega))};\]
\[\text{max\_COP\_y\_position\_global} = \text{max(COP\_y\_position(TtC\_sample\_alpha:TtC\_sample\_omega))};\]

\[\text{COP\_Area} = |\text{max\_COP\_x\_position\_global} - \text{min\_COP\_x\_position\_global}| * |\text{max\_COP\_y\_position\_global} - \text{min\_COP\_y\_position\_global}|;\]

\%
\text{Temporal}
\text{for} \ ctr = 1:\text{num\_of\_epochs} \n\text{min\_COP\_x\_position} = |\text{min(COP\_x\_position(floor(TtC\_sample\_alpha + (ctr-1)*epoch\_length):floor(TtC\_sample\_alpha + (ctr*epoch\_length))))}|;\n\text{min\_COP\_y\_position} = |\text{min(COP\_y\_position(floor(TtC\_sample\_alpha + (ctr-1)*epoch\_length):floor(TtC\_sample\_alpha + (ctr*epoch\_length))))}|;\n\text{max\_COP\_x\_position} = |\text{max(COP\_x\_position(floor(TtC\_sample\_alpha + (ctr-1)*epoch\_length):floor(TtC\_sample\_alpha + (ctr*epoch\_length))))}|;\n\text{max\_COP\_y\_position} = |\text{max(COP\_y\_position(floor(TtC\_sample\_alpha + (ctr-1)*epoch\_length):floor(TtC\_sample\_alpha + (ctr*epoch\_length))))}|;\n\text{COP\_Area\_over\_epoch(ctr) = |max\_COP\_x\_position - min\_COP\_x\_position| * |max\_COP\_y\_position - min\_COP\_y\_position|};\n\text{end}\n%
\text{Save Data}\n\text{save(sprintf('%s-NEW.mat',filename), '-v6');}\n%
\text{Create Spreadsheet}\n\text{if} \ counter==1, \n\text{columnheaders = ...};\n\{'Subject', 'Description', 'Stancefoot', 'filename'...\}
\'Max Reach Distance [mm]', 'Time to Contact (s) Epoch 1', 'Time to Contact (s) Epoch 2'...
\'Time to Contact (s) Epoch 3', 'Time to Contact (s) Epoch 4', 'Time to Contact (s) Epoch 5'...
\'COP SD X', 'COP SD Y', 'COP SD X-Epoch 1', 'COP SD X-Epoch 2', 'COP SD X-Epoch 3'...
\'COP SD X-Epoch 4', 'COP SD X-Epoch 5', 'COP SD Y-Epoch 1', 'COP SD Y-Epoch 2', 'COP SD Y-Epoch 3'...
\'COP SD Y-Epoch 4', 'COP SD Y-Epoch 5', 'Mean COP Excursion X', 'Mean COP Excursion Y'...
\'Max COP Excursion X', 'Max COP Excursion Y', 'COP Excursion X-Epoch 1', 'COP Excursion X-Epoch 2'...
\'COP Excursion X-Epoch 3', 'COP Excursion X-Epoch 4', 'COP Excursion X-Epoch 5'...
\'COP Excursion Y-Epoch 1', 'COP Excursion Y-Epoch 2', 'COP Excursion Y-Epoch 3'...
\'COP Excursion Y-Epoch 4', 'COP Excursion Y-Epoch 5', 'Total COP Excursion'...
\'Mean COP Velocity X', 'Mean COP Velocity Y', 'Max COP Velocity X', 'Max COP Velocity Y'...
\'COP Velocity X-Epoch 1', 'COP Velocity X-Epoch 2', 'COP Velocity X-Epoch 3', 'COP Velocity X-Epoch 4'...\n\text{end}
for i=1:length(columnheaders);
fprintf(fid,'%s \
',columnheaders{i});
end
fprintf(fid,'\n');
end

%% Display %thistrial=load(filename);

fprintf(fid,'"%s"	', subjectname);
fprintf(fid,'"%s"	', My_Description);
fprintf(fid,'"%s"	', stancefoot);
fprintf(fid,'"%s"	', filename);

tap = exist('tap_reach_distance');
if tap == 0
fprintf('\t');
else
fprintf(fid,'%d \	', tap_reach_distance);
end
for x = 1:5
fprintf(fid, '"%d"	', TtC_over_epoch(x));
end
fprintf(fid, '"%d"	', SD_x);
fprintf(fid, '"%d"	', SD_y);
for x = 1:5
fprintf(fid, '"%d"	', StandDev_x_over_epoch(x));
end
for x = 1:5
fprintf(fid, '"%d"	', StandDev_y_over_epoch(x));
end
fprintf(fid, '"%d"	', mean_COP_Exc_x);
fprintf(fid, '"%d"	', mean_COP_Exc_y);
fprintf(fid, '"%d"	', max_COP_Exc_x);
fprintf(fid, '"%d"	', max_COP_Exc_y);
for x = 1:5
fprintf(fid, '"%d"	', COP_Exc_x_over_epoch(x));
end
for x = 1:5
fprintf(fid, '"%d"	', COP_Exc_y_over_epoch(x));
end
fprintf(fid, '"%d"	', Total_Exc);
fprintf(fid, '"%d"	', avg_CoP_x_velocity);
fprintf(fid, '"%d"	', avg_CoP_y_velocity);
fprintf(fid, '"%d"	', max_CoP_x_velocity);
fprintf(fid, '"%d"	', max_CoP_y_velocity);

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for x = 1:5
fprintf(fid, ""%d"	", COP_Vel_x_over_epoch(x));
end
for x = 1:5
fprintf(fid, ""%d"	", COP_Vel_y_over_epoch(x));
end
fprintf(fid,"%d"	, COP_Area);
for x = 1:5
fprintf(fid, ""%d"	", COP_Area_over_epoch(x));
end
fprintf(fid,"
");
end
disp('spreadsheet complete')

ANOVA

% ANOVAN for Epoch =
f(Condition,Side,Direction,Subject,EpochNum,TestOrder)
% Use with 'SEBT_TtCandTradMeasures_summarydata.mat'
% Created 5 April, 2012

% % TtC: Side, Condition, Direction, Subject, Epoch - with side-epoch interaction and
% % direction-epoch interaction
[pYTtC,tYTtC,stats_YTtC] = anovan(TtC5(:,{Side5(:) Condition5(:)
Direction5(:) Subject5(:) Epoch5(:)}},'random',4,'model',[1 0 0 0 0; 0 1 0
0 0; 0 0 1 0 0; 0 0 0 1 0; 0 0 0 0 1; 1 0 0 0 1; 0 0 1 0
1],'varnames',{"Side','Condition','Direction','Subject','EpochNumber'});

% % TtC: Side, Direction, Subject, Epoch - with side-epoch and direction-
epoch interaction
[pYTtC,tYTtC,stats_YTtC] = anovan(TtC5(:,{Side5(:) Direction5(:)
Subject5(:) Epoch5(:)}),'random',2,'model',[1 0 0 0; 0 1 0 0; 0 0 1 0; 1 0
0 1; 0 1 0 1],'varnames',{"Side','Direction','Subject','EpochNumber'});

Post-hoc Tukey’s HSD Comparison

%% Multcompare and NormalizedPlots_for_TtCandTraditionalMeasures
% Created 6 April 2012 by SAS

%% Multcompare
% % Epoch
[cYTtC_epoch,mYTtC_epoch,hYTtC_epoch] =
multcompare(stats_YTtC,'dimension',[5]);
Correlation Analysis

%% Regression_TtC_Reach.m
% Created by SAS on 17 April 2012

cic; clear;

load('SEBT_TtCandTradMeasures_summarydata.mat')

[RHO, PVAL] = corr(TtC5_ant_posm_posl, norm_reach_ant_posm_posl)

[RHO_s, PVAL_s] =
corr(TtC5_ant_posm_posl, norm_reach_ant_posm_posl,'type','Spearman')
APPENDIX B: EQUATIONS FOR CALCULATING TTC

The following equations developed by Slobounov, et al. (1997) were used to calculate TtC.

*Instantaneous Trajectory of the Center of Pressure*

The virtual trajectory is parameterized by the time variable $\tau$.

\[
x(\tau) = r_{ox}(t_i) + v_{ox}(t_i)\tau + \frac{a_{ox}(t_i)\tau^2}{2}
\]

\[
y(\tau) = r_{oy}(t_i) + v_{oy}(t_i)\tau + \frac{a_{oy}(t_i)\tau^2}{2}
\]

where $r_{ox}$ and $r_{oy}$, $v_{ox}$ and $v_{oy}$, and $a_{ox}$ and $a_{oy}$, are the instantaneous x and y positions, x and y velocities, and x and y accelerations of the COP at time $t_i$, respectively.

*Stability Boundary Equations*

\[
y - y_c = m(x - x_c)
\]

Where $x_c$ and $y_c$ are the x and y coordinates of one of the endpoints of the line and $m$ is the slope of the line.

*Quadratic Equation Achieved from Algebraic Rearrangement*

\[
A\tau^2_c + B\tau_c + C = 0
\]

where,

\[
A = \frac{a_{oy}(t_i) - ma_{ox}(t_i)}{2}
\]

\[
B = v_{oy}(t_i) - mv_{ox}(t_i)
\]

\[
C = r_{oy}(t_i) - y_c - m(r_{ox}(t_i) - x_c)
\]
REFERENCES


