ABSTRACT

Title of Thesis: THE RELATIONSHIP BETWEEN TOUCH AND INFANTS' UPRIGHT POSTURE DURING THE FIRST YEAR OF WALKING

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Much of the research on postural development has focused on changes in trunk and lower limb control. However, the hands may also play an integral role as young infants learn to stand and walk. In this study, we examine the hypothesis that with increasing walking experience infants improve their ability to use the hand adaptively for postural control. Six infants were studied longitudinally from 1-month pre-walking to 9-months post-walking while they stood touching a static contact surface. Touch forces (TF) were examined across 10 confidence ellipses each containing 10% of the infants' postural sway. The results indicated that as infants gained walking experience they applied more TF the farther they were away from their postural center. With development, infants gain an understanding of their body position and use touch differently depending on their current position relative to their "functional boundaries".

THE RELATIONSHIP BETWEEN TOUCH AND INFANTS' UPRIGHT POSTURE DURING THE FIRST YEAR OF WALKING

by

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CHAPTER 1

INTRODUCTION

Acquiring and maintaining upright stance is a relatively difficult task for infants with top-heavy bodies. It takes infants about 11 months to acquire independent upright bipedal stance and it is not until the end of the first year that infants can remain upright independently with a moving base of support (i.e. walking). How the postural control system changes with development and what the mechanisms are underlying those changes have attracted many researchers' attention.

Much of the research on the development of postural control has focused on the postural development of the trunk and lower limbs. However, in infants, the hands can play an integral part in learning to stand and walk. Previous studies have suggested that infants use their hands to provide both physical support and spatial information for postural control (Barela, Jeka, & Clark, 1999; Metcalfe & Clark, 2001). Barela et al., (1999) for example, demonstrated that infants who have just begun to pull themselves to a stand, use the hand for mechanical support. However, these studies do not reveal under what circumstance infants use their hands for mechanical support and when they use them for information (i.e. their touch strategy). To fully understand the role of hand use in the development of the upright stance, the previous work needs to be extended to an examination of the touch strategies infants apply and how those strategies change with development.

The purpose of the present study, therefore, is to examine how infants use their hands in controlling upright stance. We examined this issue by using analyses that looked at the within-trial dynamic relationship between hand touch and postural sway in addition to the general relationship between these two variables.

This thesis is organized into fourth chapters. This introductory chapter is the first. The second chapter presents a review of the literatures that are related to the development of upright postural control and the role of hand use in upright stance. The third chapter represents the full text of the experiment including the rationale, methods, results, and discussion of findings. The last chapter offers suggestions for future research.

CHAPTER 2

REVIEW of LITERATURE

The purpose of this chapter is to review the literature related to the development of hand use in upright postural control. This chapter is organized into three main sections. The first section broadly introduces upright postural control. The second section reviews the role of hand use in upright stance in both adult and infants. A potential factor that influences hand use, relative stability, is discussed in the last section.

Postural Control.

Before discussing the role of hand use in developmental upright postural control, we first need to discuss some basic elements of the postural control system and its development. In this general postural control section, we discuss the basic postural control system and the developmental changes associated with upright stance.

The postural control system includes all the sensorimotor components involved in organizing two important behaviors: postural orientation (postural alignment) and postural equilibrium (postural balance) (Horak & Macpherson, 1996). Postural orientation is the maintenance of the relative position of body segments with respect to each other and to the environment, while postural equilibrium is the balance state in which the body stabilizes all the external and internal forces. Achieving these two behavioral goals requires first, the integration of three sensory systems (visual, vestibular and somatosensory systems), which can provide a representation of the configuration of the body segments with respect to the external world (Gurfinkel, Levik, Smetanin, &

Popov, 1988). The idea that the postural system uses a representation or estimation of spatial orientation is consistent with numerous conceptions of the postural control system (Borah, Young, & Curry, 1988; Jeka, Oie, & Kiemel, 2000; Kiemel, Oie, & Jeka, 2002; Merfeld, Young, Oman, & Shelhamer, 1993). Second, achieving the behavioral goals requires the ability to generate forces for controlling and coordinating body position on the basis of information from the body representation, thus requiring the integration of the motor and sensory systems. In sum, the postural control system is viewed as the complex interactions among multiple systems, which includes the sensory information systems needed to estimate the body state relative to the environment and the musculoskeletal system needed to control body segments in a coordinated way.

<u>Developmental of upright postural control.</u> Given the complexity of the postural control system, it is not difficult to imagine that the acquisition of upright stance is a relatively demanding and challenging task for human infants. Infants not only have to develop the ability to use and interpret the information from the sensory system but they must integrate the various sensory systems with the musculoskeletal system underlying the behavioral goals of posture. It takes infants about 11 months to acquire independent upright bipedal stance and it is not until the end of the first year that infants can remain upright independently with a moving base of support (i.e. walking). These general markers of the movement capacities of infants, known as motor milestones, have been described in detail in the developmental research. Yet, while the development of postural and locomotion milestones have been well documented (Bayley, 1993), key questions remain regarding developmental changes in the postural control system and the mechanisms underlying these changes.

One key question involves the role of sensory information in the development of postural control. While sensory information is important for infants to improve postural abilities, several different hypotheses have been proposed for the mechanisms that underlie how infants use sensory information. Woollacott and Shumway-Cook (1985) suggest that the improvements in the integration of the different sensory systems leads to more mature postural control responses. They also suggest that the relationship between sensory inputs and motor outputs must be established and the connections strengthened and fine-tuned with development (Sveistrup & Woollacott, 1996). Forssberg and colleagues (Forssberg & Nashner, 1982; Hirschfeld & Forssberg, 1994) propose that the development of postural control is not restricted to the development of sensory or motor systems, but is associated with the development of central mechanisms responsible for integrating sensory inputs into appropriate motor commands. A third hypothesis suggests that a critical factor underlying the development of posture is the establishment of a coherent and functional perception-action relationship (Barela et al., 1999; Bertenthal, Rose, & Bai, 1997; Metcalfe et al., 2001). According to this hypothesis, understanding how infants manage their multi-segmented bodies while moving in an ever-changing environment requires understanding the relationship between sensory information and motor action. These three hypotheses emphasize the crucial role of sensory inputs on the developmental aspects of upright postural control; however, the differences in these perspectives suggest more questions remain.

A predominant paradigm used to examine the role of sensory information in the development of upright postural control is to record postural responses following a perturbation (Assaiante, Woollacott, & Amblard, 2000; Forssberg, 1985; Forssberg et al., 1982; Roncesvalles, Woollacott, & Jensen, 2001; Shumway-Cook & Woollacott, 1985; Sveistrup et al., 1996). For example, patterns of muscle activity from the trunk and lower limbs are examined in response to a brief perturbation of the infant's body or the sensory environment; for example, the platform the infant is standing on is quickly moved backward. While this paradigm has revealed numerous developmental changes, one deficiency in this paradigm is that only the response patterns to these discrete perturbations are examined, which does not capture postural control during continuous adaptations to every-changing environment contexts. Further, the majority of studies focus on recording movements from the primary postural muscles (trunk and lower limbs) with little attention to the contribution of the hand in controlling upright stance. Developmentally, it is known that infants naturally use their hand to support their posture when they learn to stand and walk. Young infants rely not only on their lower limbs but also use their upper body (including hand use) to maintain their upright stance. Besides the importance of hand use in early upright postural control, hand use by infants adds an additional level of complexity to upright stance. For example, the hand can be used for mechanical support and as a source of information. Examining the hand use during upright stance may open a new window to understanding the relationship between sensory information and motor action.

The Role of Hand Use in Upright Postural Control.

In postural control, hands are used to exploit objects in the environment for both mechanical support and as a source of information. To fully understand the development of upright stance, examining how infants use their hands to maintain upright stance is important. The following subsections will discuss these two major roles of hand use in controlling upright stance in adults and then in studies of hand use in the development of upright postural control.

<u>Mechanical support.</u> In everyday life, there are many situations in which hands are used mechanically to support upright stance. Take, for example, riding in a crowed subway, when the car suddenly breaks, many of us immediately grasp a chair or handle to get support and prevent falling. Evidence of hand use as mechanical support during the maintenance of upright stance has been shown in several studies. In adults, Cordo and Nashner (1982) demonstrated that when a hand was used to provide support during ground surface perturbations, a "leg-like" pattern of muscle activation was found in the arm concurrent with decreased muscular activity in the lower limbs. The authors suggested that “automatic postural adjustments can be elicited in any muscle that the subjects, through the postural set, have perceived to be functionally useful in maintaining equilibrium (p. 297)”. In a similar study, Maki and Mcllroy (Maki & McIlroy, 1997) studied grasping reactions that serve to increase external support during platform translations. They found that the activity in the shoulder muscles appeared early, 90 to 140 milliseconds after onset of perturbation, which is very similar in the timing to the postural response in the ankle muscles (e.g. ankle strategy responses).

Evidence of mechanical support is found when adults only use a single fingertip to touch a surface (Jeka & Lackner, 1994; Jeka & Lackner, 1995). During upright stance, when participants could apply as much single fingertip force as desired, the mean touch force was observed to be 5 N and body sway was significantly decreased compared to that in the no-touch condition. The amount of applied touch force and the temporal relationship between the applied touch force and postural sway (in-phase relationship) suggested that adults used touch for mechanical stabilization of their upright stance. One shortcoming of this analysis is that the authors only examined the mean touch force in a trial which could not detect moment to moment changes in touch force. Unfortunately, the authors did not report whether the participants applied mechanical support continuously or only during the moment of instability. In sum, the evidence clearly suggests that the hand is used to mechanically support upright stance by adults in particular task settings. However, how adults use the hand for mechanical support (the nature of the utility of mechanical support) is not well understood.

Sensory information. The second role for the hand in postural control is to provide sensory information, not only from cutaneous touch receptors but also from proprioceptors in the finger, elbow and shoulder joints. This information, along with other sensory modalities, is important for perceiving the body configuration together with its relationship to the external world (Horak et al., 1996; Massion, 1998). Evidence for the role of somatosensory information in postural control has been gained through a series of studies using a light touch paradigm (Jeka et al., 1994; Jeka et al., 1995). In these studies, participants stood in a heel-to-toe tandem Romberg stance while lightly touching a support surface with the tip of the index finger. The authors compared upright postural sway in this light touch condition and a control condition (participants stood without touching the support surface). They found that although the contact forces (< 1N) were smaller than that required for physical mechanical support, the postural sway in the light touch condition was effectively attenuated by over 60% from the control condition. The temporal relationship between body sway and applied touch force showed that in the light touch condition, the changes in the fingertip force led body sway by approximately 300 ms. This time change is long enough for the sensory cues via the fingertip to be used to detect postural sway from the combination of changes in fingertip forces and the position of the fingertip relative to the rest of the body. Thus, it is argued that this sensory cue provides feedforward control in the postural control system (Jeka et al., 1994). In a further study, Jeka and Lackner (1995) examined EMG activity in the leg muscles and observed that the EMG activity occurred around 150 ms behind the change of the touch force and around 150 ms ahead of body sway. This finding supports the conclusion that the touch sensory cue was used to reduce body sway through postural muscle activation (Jeka et al., 1995). Recently, Clapp and Wing (Clapp & Wing, 1999) extended Jeka's results to normal bipedal stance, suggesting that the utility of hand touch inputs is used in the more stable bipedal stance as well. Taken together, these studies demonstrate that adults can use their hand as a source of information that contributes to upright postural control.

Hand use in the development of upright postural control. In early postural control, the hand is obviously used for mechanical support. That is, young infants are often observed using their hands to hold onto a chair or table to get support when they are learning to stand and walk. For infants, the hand is a natural and important assistant to acquiring the newly emerging posture. This behavior is specifically critical in the infant's ability to pull to stand and during the precursor to bipedal locomotion, cruising. However, the experimental evidence of how infants use mechanical support during the development of upright stance is limited. Furthermore, studying the hand's use of sensory information independent of mechanical support is difficult to experimentally examine in early postural control. In the adults' light touch paradigm, participants are instructed not to apply touch forces larger than one N with a single fingertip. However, it is not possible to have young infants follow this specific task requirement. Rather, a modified touch paradigm has been used in the developmental research in which infants may touch the contact surface with more than the fingertip, but not grasp the touch surface. Within these constraints, several studies have attempted to assess hand use and its development in "natural" situations where infants could use both mechanical support and sensory information.

Using a moving platform perturbation, several studies have examined the postural muscle response of infants who stood with manual support (Sveistrup et al., 1996; Woollacott & Sveistrup, 1992). That is, these studies examined the activity of trunk and lower limb muscles of young infants who could not maintain upright stance without the hand contacting a support object. Although the authors did not examine the muscular responses from the upper limbs, they suggested that in these studies young infants may have used alternative postural strategies that incorporate the stability and control provided through the upper body. Stroffergen and his colleagues (Stoffregen, Adolph, Thelen, Gorday, & Sheng, 1997) studied the utility of manual control in young infants with a few weeks of standing experience during upright stance under varying support surface conditions (differed in length, friction, and rigidity). Hand use was shown to increase (as measured by time on touch surface) with greater instability of the ground surface. The authors suggest that manual control is an adaptive strategy for postural control. However, how the hand touched the surface and how hand use changed developmentally were not examined in this study.

Using the modified touch paradigm within a longitudinal design, Barela et al (1999) demonstrated that hand use changes across walking age by observing changes in both mean touch force (TF) and the temporal relationship between TF and postural sway. The authors studied four developmental periods related to infants' motor milestones: pull to stand (PS), stand alone (SA), walking onset (WO) and 1.5 months post walking (PW). By observing vertical touch forces, the authors found that infants used contact forces (about 10 N) to support their upright stance during the PS developmental period, and decreased touch vertical forces (about 5 N) were found during the later three periods. The temporal relationship between body sway and touch force indicated that in infants during the PW period, touch force led body sway by about 140 ms, while in the other three periods, touch force and body sway were almost in phase. The authors interpreted these results to mean that young infants first used their hands for mechanical support and as they developed, potentially due to the increased muscle strength of the lower limbs, infants no longer used large amounts of external support for assistance. The changes in the time lag was interpreted as indicating the infants in the PW period no longer used mechanical support but rather they used the touch input as a sensory cue to enhance postural control like adults. However, considering that when infants had increased experience in the upright, they still applied large amounts of TF compared with light touch in adults (~ 5 N), other interpretations such as age-related changes in the type of mechanical support or age-related changes in the amount of time that mechanical support is applied must be considered. Thus, while Barela et al. (1999) demonstrated that hand use is largely mechanical in early developmental postural control and changes with experience in the upright, further examination of how infants use their hand (i.e. a touch strategy) is warranted.

In a cross-sectional study, Metcalfe et al. (2001) studied how three groups of walking infants (walking ages: 1-4 months, 5-8 months and > 9 months) used a touch surface in the control of upright stance. They examined infants' body sway and the temporal coordination between three body markers (head, shoulder, and center of mass) in upright standing under both no touch and hand touch conditions (modified touch paradigm). The results across all three age groups showed during touch (1) a sway attenuation effect and (2) decreased correlation coefficients between body segments. These finding indicated that across the three cross-sectional groups of infants who had been walking from one to the twelve months, (1) touch sensory information could be used to stabilize their posture, and (2) infants behaviorally explored the relationship between the incoming touch sensory information and their posture. However, in this study, how the hand touched the surface was again not examined. The authors did not measure the touch forces that infants and toddlers applied but only controlled the upper limit of the force they could apply (< 10 N). While Metcalfe et al. (2001) demonstrated that young infants and toddlers use touch information to attenuate sway, they did not clearly reveal how infants and toddlers use their hands to control upright stance.

In conclusion, the importance of using the hand to touch a contact surface to control upright stance in infants and toddlers was demonstrated in several prior studies. Yet to fully understand the development of the upright stance, these findings need to be extended to an examination of the touch strategies infants utilize over time and in relation to their body sway and how these strategies change with development.

Hand Use vs. Relative Stability of Upright Stance.

Understanding the development of touch strategies requires considering why infants use their hands during upright stance. Stoffregen and his colleagues (Stoffregen et al., 1997) argued that young infants use their hands adaptively to stand upright. That is, by changing the conditions of the support surface experimentally, the authors found that newly walking infants use their hands to hold onto something if their bodies are unstable (i.e. relatively unstable support surface), but remain hands-free if their bodies are stable. Stoffregen's research suggests that relative stability is a crucial factor that influences hand use during upright stance. To examine how hand use may be associated with relative stability, we first need to understand the basic concept of postural stability and ultimately the touch strategies infants apply during upright stance.

Stability of Upright Stance. It is generally recognized that maintaining upright stance requires the center of mass (COM) of the body to be positioned within the base of support. The boundaries of upright stance, called stability limits have been defined by McCollum and Leen (1989) as the range of postural states within which both voluntary movement and imposed perturbation occur without causing instability (i.e. falling or taking a step). These boundaries are a result of the limitation of body mechanical constraints. Quantitative measures of postural stability have traditionally focused on the examination of COM variance and horizontal distance of COM relative to the boundaries of the feet. While much of the research has evaluated COM position's importance for the control of balance, increasingly studies suggest that controlling velocity and/or the integration between position and velocity is important for postural stability (Jeka, Oie, Schöner, Dijkstra, & Henson, 1998; Pai, 2003; Pai & Patton, 1997; Shumway-Cook &

Woollacott, 2001; van Wegen, van Emmerik, & Riccio, 2002) . That is, upright stance cannot be maintained under conditions of large COM velocity even if COM position is within the base of support (Pai, 2003; Pai et al., 1997).Additionally, the stability of upright stance has also been linked to both position and velocity of center of pressure (COP) (van Wegen et al., 2002). The term “relative stability” is used to reflect the likelihood that upright posture can be maintained. The evidence presented here suggests that relative stability decreases with increased position and velocity. That is, when a person’s body position is close to the edge of the boundary, he or she is more likely to fall (more unstable). Similarly, when a person has higher velocity sway at any point within the boundaries, his or her body is moving faster toward a boundary, which may cause instability of upright stance.

When someone becomes relatively unstable, postural stability needs to be regained through muscular contractions or limb movements (i.e. a step by foot or a grasp by hand) (Maki et al., 1997). The second strategy suggests a potential relationship between hand use and stability. While this potential relationship may exist in infants, the feasibility of this idea depends on infants having knowledge about their own stability which depends on the integration of peripheral sensory inputs. Several studies have demonstrated that stability boundaries and one’s postural state relative to its boundaries can be perceived in adults, although not necessarily consciously (Riccio & Stoffregen, 1988; van Wegen et al., 2002). McCollum and Leen (1989) suggests that infants discover their stability limits as they learn to stand and gain experience in the upright. Thus, it seems feasible that infants would use a hand strategy that would depend on the perceived postural state (the relative stability).

Relationship Between Hand Use and Stability. Developmentally, it is known that young infants are highly unstable and they have to use mechanical support to keep themselves upright. Infant development is associated with marked increases of stability in upright stance that occur concurrently with reductions of applied mean touch force (Barela et al., 1999). Barela et al. (1999) interpreted the reduction of mean TF as a decrease in the amount of mechanical support needed for maintaining upright stance. However, how the amount of mechanical support was proposed to decrease was unclear. For example, the amount of mechanical support could be decreased in general as indexed by constant TF reductions across entire trials. Alternatively, the reduction could result from infants continuing to use a strategy in which they use mechanical support only when their bodies are unstable while the time in which they use *mechanical*su pport decreases. This second strategy could allow for the infants to use their hands for another purpose, such as for informational use, while their bodies are relatively stable. Thus, based on the second strategy, infants may apply a touch strategy wherein hand use is dependent on perceived postural state. That is, infants use touch primarily for mechanical support when they are unstable and primarily for sensory information when stable. However, there is no current research addressing this potential touch strategy for upright postural control or how the strategy changes with development. One possible reason is because the summary measures that these studies used (i.e. mean touch force) are not sufficient to examine a strategy which changes across time.

In summary, to understand how infants use their hand during the development of upright postural control, an examination of the dynamic relationship between hand use and relative stability is needed. Considering the important parameters of the postural control system, both position and velocity of postural sway should be applied to define the relative stability. Further, the examination of hand use strategies when the infant is relatively unstable would provide insight into the touch strategies infants used and potentially lead to an extended understanding of developmental upright postural control.

CHAPTER 3

THE RELATIONSHIP BETWEEN TOUCH AND INFANTS' UPRIGHT POSTURE DURING THE FIRST YEAR OF WALKING

INTRODUCTION

The ability to manipulate oneself and objects in the environment is dependent on having a stable posture. As such, the development of postural control is crucial to the acquisition and refinement of voluntary skills. One approach for studying the development of upright posture focuses on compensatory responses in the primary postural muscles (i.e. trunk and lower limbs) after external perturbations (Forssberg, 1985; Forssberg et al., 1982; Sveistrup et al., 1996; Woollacott, Debu, & Mowatt, 1987). However, maintenance of upright stance is not restricted to the trunk and lower limbs. Young infants also use their hands as they learn to stand upright and walk. For example, for infants with minimal walking experience, the hand has been shown to be adaptively used to control posture in conditions of varying support surface stability (Stoffregen et al., 1997). Further, how the hand is used with respect to upright postural control has been shown to change with experience in the upright (Barela et al., 1999). While these studies have demonstrated the importance of hand use during the development of upright postural control, there are many aspects of hand usage in postural control that have not been explored. For example, it is unclear whether infants apply a constant but noisy touch force or if they dynamically alternate their touch force based on their body's position. In this paper, we will explore several issues regarding the role of the hand in postural control and the development of hand use strategies as infants gain experience in upright stance.

During the development of upright posture, infants use their hands to exploit objects in the environment (i.e. tables, chairs) for both physical support and informational sources for controlling upright stance (Barela et al., 1999; Metcalfe et al., 2001). To effectively use the hand for both mechanical and informational purposes, individuals must develop a strategy that balances these two roles of the hand. Evidence for strategies involving mechanical support has been found in both adults and infants. That is, adults and infants clearly place their hands on rigid surface/objects for mechanical support in real life situations. This behavior is specifically critical during the development of upright stance; pull to stand (PS), and during the precursor to bipedal locomotion, cruising. Experimental studies of adults have demonstrated that when a hand was used to provide support during ground surface perturbations, a "leg-like" pattern of muscle activation was found in the arm concurrent with decreasing muscular activity in the lower limbs (Cordo & Nashner, 1982). Evidence of mechanical support is found even when adults use only a single fingertip to touch a surface where they could apply as much fingertip touch force as desired (Jeka et al., 1994; Jeka et al., 1995). The amount of applied touch forces and the temporal relationship between the applied touch force and postural sway suggested that adults use touch for mechanical stabilization of their upright stance. Taken together, these studies clearly suggest that the hand is used to mechanically support upright postural control by both adults and infants in particular task settings.

The other role for the hand in postural control is to provide sensory information, not only from cutaneous touch receptors but also from proprioceptors in the finger, elbow and shoulder joints. This information, along with other sensory modalities, is important for perceiving the body configuration together with its relationship to the external world (Horak et al., 1996; Massion, 1998). Evidence for the role of somatosensory information in postural control has been gained through the use of the light touch paradigm (Jeka et al., 1994; Jeka et al., 1995). In this paradigm, in order to exclude the effect of mechanical support from hand use, participants were asked to apply touch force (TF) smaller than one N with a single fingertip. Although the TF was small (~0.1N), postural sway during light touch conditions was attenuated by over 60% as compared with no touch conditions. The authors argued that the sensory cues from the fingertip could detect and aid the control of postural sway from the combination of changes in fingertip forces and the position of the fingertip relative to the rest of the body. While the light touch paradigm has been successful in adults, the application of the same paradigm to infant research is not possible. Riccio and Stoffregen (1997) proposed that the goals of the organism impose the most important constraints on the control of stance. For the adults, the goal of the participants is to perform the task as instructed, for example, maintaining upright stance with light touch. Yet, it is nearly impossible to experimentally control infants' goals and therefore the amount of contact force they intentionally apply. Therefore, in order to understand the informational role of infant hand use in postural control, a paradigm must be developed that assesses the possible roles of the hand in an ecologically valid situation.

Several studies have attempted to assess hand use and its development in "natural" situations where infants could use both mechanical support and sensory information. Stoffregen et al. (1997) conducted a cross-sectional study to examine the role of infants’ hand use in upright stance under conditions of differing ground support surfaces. Hand use was shown to increase (as measured by time on touch surface) with greater instability of the ground surface. However, how the hand touched the surface and how the hand use changed developmentally were not examined in this study. In a longitudinal study, Barela et al (1999) demonstrated that hand use changes across walking age by observing changes in both mean TF and the temporal relationship between TF and postural sway. One interpretation of these observations is that the touch strategy switched from mechanical support to informational use with increasing experience in the upright posture. However, considering that when infants had increased experience in the upright, they still applied large amounts of TF (> 5 N), other interpretations such as age-related changes in the type of mechanical support or age-related changes in the amount of time that mechanical support is applied must be considered. In a third study, Metcalfe and Clark (2001) examined the effects of hand touch for controlling upright stance by comparing changes of body sway and coordination among body segments in touch and no touch conditions. The authors suggested that across three cross-sectional groups of newly walking infants and toddlers, touch was used as a source of information for the attenuation and exploration of postural sway. However, again, the authors did not examine the touch strategies employed by infants. In all three of these studies, the importance of using hand touch in the control of upright stance was demonstrated. Yet to fully understand the development of the upright stance, this work needs to be extended to an examination of the touch strategies infants apply and how those strategies change with development.

Understanding the development of touch strategies requires the consideration of why infants use their hands during upright stance. It is known that newly walking infants use their hand to hold onto something if their bodies are unstable but remain hands-free if their bodies are stable (Stoffregen et al., 1997). Stability of upright stance thus seems to be an important factor that influences hand use. Developmentally, it is known that initially, infants are completely unstable, and they have to use mechanical support to keep themselves upright (PS stage). As infants develop, increased periods of stability in upright stance are observed concurrent with reductions of mean TF (Barela et al., 1999). Barela et al. interpreted the reduction of mean TF as a decrease in the amount of mechanical support needed for maintaining upright stance. However, how the amount of mechanical support was proposed to decrease was unclear. For example, mechanical support could be decreased in general as indexed by a constant TF reduction across the entire trial. Alternatively, the reduction could result from infants continuing to use a strategy in which they use mechanical support only when their bodies are unstable (with the time which they are using mechanical support decreasing). This second strategy could allow a shift in the primary role of the hand to serve another purpose such as for informational use, while their bodies are relatively stable. However, this potential strategy depends on infants having knowledge of their own stability. Support for the feasibility of this idea comes from several studies demonstrating that postural state is detected during the upright stance (McCollum & Leen, 1989; Riccio et al., 1988; van Wegen et al., 2002) and that infants discover their stability limits as they learn to stand and gain experience in the upright (McCollum et al., 1989). The differences in potential strategies outlined above suggest that it is important to measure the changes in TF relative to postural state. The summary measures used in previous studies (such as mean TF, etc) are not sufficient to examine the changes in touch strategies as they obscure the dynamic relationship between TF and body position. An examination of the relationship between touch forces and posture as it changes dynamically over the course of a trial may differentiate between the potential strategies and thus provide insight into understanding infants' touch strategy during upright stance.

In this study, we examine the dynamic relationship between hand use and postural sway with a focus on the within-trial dynamic interaction to test if infants' hand use is dependent on their postural state. Our general hypothesis is that infants apply a touch strategy wherein hand use is dependent on perceived postural state. That is, infants use touch for mechanical support when they are unstable while they use sensory information when both stable and unstable. Developmentally, with the increased experience in upright stance, we propose that infants will better estimate their stability, which will lead to a more accurate application of the touch strategy. As it has been suggested that position and velocity are both important for postural control (Jeka et al., 1998; Jeka, Schoner, Dijkstra, Ribeiro, & Lackner, 1997; Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996; van Wegen et al., 2002), we examined both position and velocity as our relative stability measures. We defined unstable and stable regions as relative terms that refer to large absolute positions/velocities and small absolute positions/velocities respectively.

METHODS

Participants.

Six infants (3 male; 3 female), who participated in a larger longitudinal study, were used for this research. The infants were recruited from the University of Maryland, College Park, area and its surrounding communities. All infants were healthy, full-term, and normally developing as assessed by the Bayley Scales of Infant Development, 2nd edition (Bayley, 1993). Infants participated in the study as soon as they could sit independently (mean age = 6.14 ± 0.86 months) and were tested every month thereafter until they reached 9 months of independent walking experience (mean age at walk onset = 10.97 ± 1.22 months). The criterion for independent walking was that infants could walk at least 3 steps without falling. For the purpose of this analysis, infants were assessed only at ages when they could maintain upright stance while using their right hand for support; specifically from 1- month pre-walk onset to 9-months post-walk onset. Each infant's parents or guardians were given oral description of the tasks and study and provided written informed consent prior to inclusion in the longitudinal protocol. All procedures of this study were approved by the Institutional Review Board at the University of Maryland-College Park.

Experimental Setup and Apparatus.

Infants stood on a small pedestal (10cm deep x 20 cm long x 11 cm tall) affixed to a force platform in a testing room (2.1 m x 5.5 m), which was enclosed by black curtains. The room was designed to reduce the distraction of the other areas of the laboratory and from the data acquisition equipment. The purpose of the pedestal was to reduce the incidence of infants walking. Figure 1 illustrates the experimental set-up, where each infant stood on a small pedestal affixed to a force platform in a parallel stance with eyes open and with the right hand in contact with the touch bar. All data were collected with a Windows NT workstation (Intergraph TDZ-2000) using a National Instruments A/D board (BNC-2090) and custom LabView data acquisition program. All signals were sampled at 50.33 Hz.

Figure 1. Illustration of the Experimental Setup.

Touch Bar Apparatus. The touch bar was mounted on an adjustable support frame, which allows for subjects of different heights. The apparatus was positioned to the right of each participant at the approximate top of the iliac crest. The contact surface was a 4.4 cm diameter convex surface, formed by the top half of a 45.7 cm long PVC tube. The convex surface was designed so as to afford touching but not grasping the surface. The contact surface was attached atop two support columns, each instrumented with force transducers (Interface MB-10) for resolving applied hand contact forces. Vertical touch forces were recorded with positive values indicating downward application of force. The entire touch bar was mounted on a precision linear positioning table (Daedal 105002BT) and driven by DC brushless motor (Compumotor SM231AE) controlled by a torque servo drive (Compumotor OEM675T).

Center of Mass (COM). Center of mass in three directions, medial-lateral (COM_{ml}), anterior-posterior (COM_{ap}), and vertical COM (COM_{v}), was measured by using a 3-D ultrasound position tracking system (Logitech, Inc). The system consists of a control unit, a small triangular sensor (7x7x7 cm), and a triangular transmitter (25x25x25 cm). The triangular sensor (referred to as the “tracker”) was affixed to the infant's lower back at the level of the fourth or fifth lumber vertebrae via lightweight Velcro and elastic waist-bands.

Procedures.

Once infants and their parents entered the laboratory, the infant was given a short period to adapt to the experimenters and the testing environment. Following the acclimation period, the infant was taken to the small testing room and introduced to a small pedestal affixed to the force platform. The infant’s shoes were removed and, once placed on the pedestal, the tracker was affixed at the level of center of mass position and the position of the touch apparatus was adjusted so that the infant's arm was abducted approximately 45°, the elbow was slightly flexed and the hand was held slightly in front of their body. For each testing session, infants completed three trials of five different conditions while they stood quietly. These conditions were presented randomly and included: no touch, touching a static bar, and touching a moving bar at frequencies of 0.1, 0.3 or 0.5 Hz, amplitudes of 1.6, 0.59, 0.36 cm respectively). All trials lasted 60 seconds except in the moving bar condition at 0.1 Hz frequency which lasted 90 sec so as to provide sufficient cycles for analysis. Based on previous research with this paradigm, the first five trials were touch conditions as we have found that if the session begins with "no touch" trials, infants are reluctant to do the "touch" trials. For the purpose of this study, only the static-touch condition was examined.

To facilitate and maintain participation in the task, an experimenter was positioned in front of the infant where he or she attempted to maintain the infant's attention with a variety of toys or books. The parent or guardian was always present and helped position the infant for each trial as well as to prevent any possible falls. To ensure that the infant performed the appropriate touch condition, a second experimenter was positioned to the infant's right side and monitored hand contact with the touch bar if needed.

All infant testing sessions were displayed on a remote television where an experimenter observed the trial for infant compliance to procedure. All trials were videotaped and synchronized with the analog data using an event synchronization unit (Peak Performance Technology and time-stamped with a SMPTE code generator-Horita

RM-50) for later behavioral coding.

Data Reduction and Measures.

Behavioral coding. In order to identify segments of data for analysis, all testing sessions were viewed independently by two trained coders who selected appropriate segments based on two main criteria: (1) infants displayed quiet standing for a minimum 10 seconds, and (2) infants continuously touched the bar but did not grasp it. The criteria for quiet standing segments were (1) no falling, bouncing or foot displacement while standing, and (2) no vigorous head, arm or trunk movements. The purpose of behavioral coding was to find the segments of data wherein infants' performance fit the experimental requirement. Only those data segments agreed to by both coders were extracted from the raw data files.

Touch forces. The vertical forces the infants applied to the touch apparatus were examined across walking ages. Randomly occurring spikes were present in the raw touch force data from an unknown source. To remove these spikes from the signal, the spikes were reduced from the raw vertical touch force (TF_v) signal (i.e., for 2-s sliding windows with 1-s overlapping, data points outside of a range of 4 standard deviations from the mean were reduced to the perimeter of that range) followed by recursive low-pass filtering (2nd order Butterworth; f_{3db} = 5 Hz). A comparison of data segments with and without spikes revealed that this process removed the effects of the analog spikes.

Absolute vertical TF (ATF_v) was calculated following spike removed. To calculate a calibrated ATF_v, the mean TF_v when the infant's hand was not on the touch apparatus was subtracted from the TF_v when the infant was touching the apparatus during a trial. Because some infants never removed their hands from the touch bar and a baseline could not be assessed, ATF_v was only calculated for 60% of the trials. To be sure that the remaining trials evenly distributed across walking age, we examined the distribution of ATF_v trials. This examination revealed that ATF_v trials were evenly distributed across walking age. To decrease between-trial variability and increase total power, in all of the trials, normalized TF_v (NTF_v) was calculated as (TF_v – minimum TF_v) / (maximum value of TF_v – minimum TF_v) within each trial.

Postural Sway. All postural sway data from COM were filtered by recursive low-pass filtering (2^{nd} order Butterworth; $f_{3db} = 5$ Hz). Both position and velocity of COM was recorded and calculated for further analysis. For postural sway position, three variables were used: two directions of COM (COM_{ml} and COM_{ap}) and the radial distance of COM (COM_{rd}, [(COM_{ml} ^2+ COM_{ap}^2)^.5]). The differentiation of position data in three directions (COM_{ml}, COM_{ap} and COM_{rd}) was calculated respectively for three variables of postural sway velocity. Furthermore, the global measure of postural sway, mean sway amplitude (MSA) and mean sway velocity (MSV) were calculated for both COM_{ml} and COM_{ap} (MSA_{ml}, $MSA_{ap,}$ MSV_{ml} and MSV_{ap}). MSA was defined by calculating the standard deviation of the postural time series data. MSV was defined by calculation of the total excursion of postural sway divided by the duration of the trial.

Correlation Analysis. To understand the general relationship between TF_v and postural response, within trial cross-correlations of (1) TF_v and postural sway position and (2) TF_v and velocity were computed for three directions ((COM_{ml}, COM_{ap} and COM_{rd}). In total, 2 x 3 (posture variables x direction) cross-correlation functions were computed. The maximum coefficient was chosen from a time period of +/- 500 msec from a zero phase lag and the corresponding time lag for the maximum coefficient was recorded. This time period was selected based on previous work in our laboratory that suggested lags longer this were uninterpretable.

Region-Related NTF$_v$. In order to examine the dynamic relationship between TF$_v$ and body sway, confidence ellipses of the postural sway and sway velocity containing 10% to 100% of the data at 10% increments were computed (see Figure 2). This analysis provides 10 regions (9 concentric ellipses and the outside region of the largest ellipse) for postural sway position and sway velocity respectively. Regions were defined from 1 to 10. For the position ellipse, 1 indicates the region from the center position to 10% of postural maximum sway. For velocity ellipse, 1 indicates the region from the zero velocity to 10% of sway maximum velocity. Following the calculation of regions of postural sway, NTF$_v$ was computed corresponding to the 10 regions of both position and velocity.

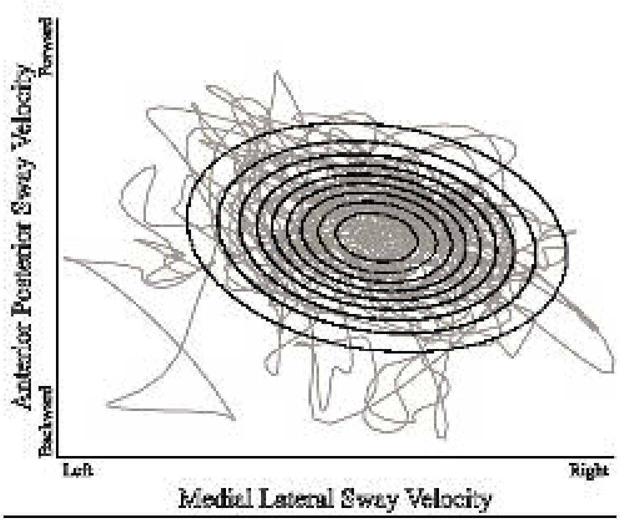


Figure 2. Confidence Ellipses of the Postural Sway. It contains 10% and 100% of the data at 10% increments. The smallest ellipse indicates 10% of postural sway data.

Statistical Analysis

Linear mixed model techniques (Proc Mixed, SAS, version 8.2) were applied for the variables associated with effect of age or both age and ellipse. The dependent variables for this analysis included (1) ATF_v, (2) MSA and MSV, (3) measures of cross-correlation: maximum coefficient and time lag, and (4) region-related NTF_v. Specifically, this mixed model analysis was completed in two parts. First, a linear mixed model analysis of variance and covariance techniques was used to decide the proper variance and covariance model/structure. Second, the appropriate variance/covariance matrix was applied to a linear mixed model regression analysis with correlated measures. These two steps of the analysis are described below:

1. Model Building: Linear mixed model analysis of variance and covariance techniques. The mixed model analysis was applied because one or two variables (age and/or ellipse) represented fixed sources of variation, while the among- and within-subject variability was attributed to random sources. Considering that age and ellipse are within-subject sources of variation (repeated measures design), the mixed model techniques also allow for control of variance heterogeneity and correlated measures within participants.

For the region-related NTF_v, the fixed portion of the model included age (11 levels), ellipse (10 levels) and age by ellipse interactions. The random portion of the model included the subject and subject by age and ellipse interactions. For the variables, ATF_v, MSA, MSV, cross-correlation coefficient and time lag, the fixed portion of model only had age effects. The random portion of the model consisted of the variance for subject and the subject by age interaction. The residual was also included as a random effect for all the above models.

To account for the correlated measures (age and/or ellipse), the mixed model techniques provided the goodness-of-fit statistic to assess how well the random portion of the model fit the residuals and provided the proper variance-covariance structure. Several covariance structure methods were examined, including compound symmetry (CS), first order autoregressive (AR1), and heterogeneous first order autoregressive (ARH1). A goodness-of-fit statistic (Akaike's Information Criterion Correction, AICC; smaller is better) was recorded from each covariance structure to find the better-fit variance-covariance structure. Heterogenous variance models were also considered for each factor. Residual variances were pooled when the AICC indicated that it was appropriate to do so.

2. Regression Analysis: Linear Mixed Model with Correlated Measures. Using the proper variance-covariance structure identified from the model building analyses, we applied a mixed model regression procedure. The fixed effects (ellipse and/or age) in the polynomial regression model were considered as continuous variables to account for their effects on the dependent variables. For the region-related NTF_v, the initial regression model contained linear, quadratic and cubic components (i.e. A, A^2 and A^3) for both age (A) and ellipse (E) and their lower order interactions. For example, the full initial model for variable NTF_v was

$$\begin{aligned} NTF_v = {} & C_0 + C_1 * A + C_2 * A^2 + C_3 * A^3 + C_4 * E + C_5 * E^2 \qquad (1) \\ & + C_6 * E^3 + C_7 * AE + C_8 * A^2 E + C_9 * A E^2 \end{aligned}$$

Wherein C_0 indicates intercept and C_1 to C_9 indicate the coefficients corresponding to each fixed effect.

For the variables only associated with age, the fixed effects in the polynomial regression model only included each set of age main effects (linear, quadratic and cubic). Reduction of the initial polynomial regression model was processed by applying the selected variance-covariance structure and variance group from the linear mixed model analysis with variance and covariance techniques. By removing the highest order non-significant terms, one at a time, the final model was reached when the highest order terms or term involving age and/or ellipse were all significant. The regression equation for the significant effects as indicated by the reduced model was generated to describe and predict the relationship between dependent and independent variables. Significant effects were assessed using planned comparisons by the method of Tukey's LSD when a final regression model containing more than a single linear effect was found. Age planned comparisons included several sets of walking days (-30 vs. 270, 30 vs. 210, 90 vs. 150). Ellipse planned comparisons included ellipse 1 vs. 10 and ellipse 3 vs. 8. For interactions, each ellipse comparison was examined for the ages (-30, 30, 90, 150, 210, and 270 in days) and each age comparison was examined for the ellipses (1, 3, 8, 10). If interactions effects were observed, the main effects were not assessed.

RESULTS

Descriptive Variables.

Three variables: absolute vertical touch force (ATF_v), mean sway amplitude (MSA), and mean sway velocity (MSV), are presented to describe the current data set. Each of these variables is examined using a regression across walking age (A). The regression analysis on ATF revealed that there was no significant age terms found in the final regression model, which indicated that there was no significant longitudinal change in ATF_v across walking ages. Mean ATF_v across all infants and walking ages was 3.822 +/- 1.21 N.

There also was no significant age term found in the final regression models for either MSA_{ml} or $MSA_{ap.}$ Theses results indicated that MSA did not change across walking age. Mean MSA_{ml} across all infants and walking ages was 0.823 +/-0.26 cm. Mean MSA_{ap} was 0.733 +/-0.17 cm.

A significant age effect was revealed in the final regression model for both MSV_{ml} and MSV_{ap}. The final polynomial models of MSV are as follows:

$$MSV_{ml} = 1.307 - 0.00142*A \text{ (cm/sec)} \qquad (1)$$

$$MSV_{ap} = 1.2688 - 0.00142*A \text{ (cm/sec)} \qquad (2)$$

In these two models, both intercept and coefficient of linear age term are significant ($p < .05$). The negative coefficient for the age effect indicates that MSV in both medial-lateral and anterior-posterior directions decreased across walking ages. Figure 3 illustrates the polynomial models for MSV_{ml} and $MSV_{ap.}$

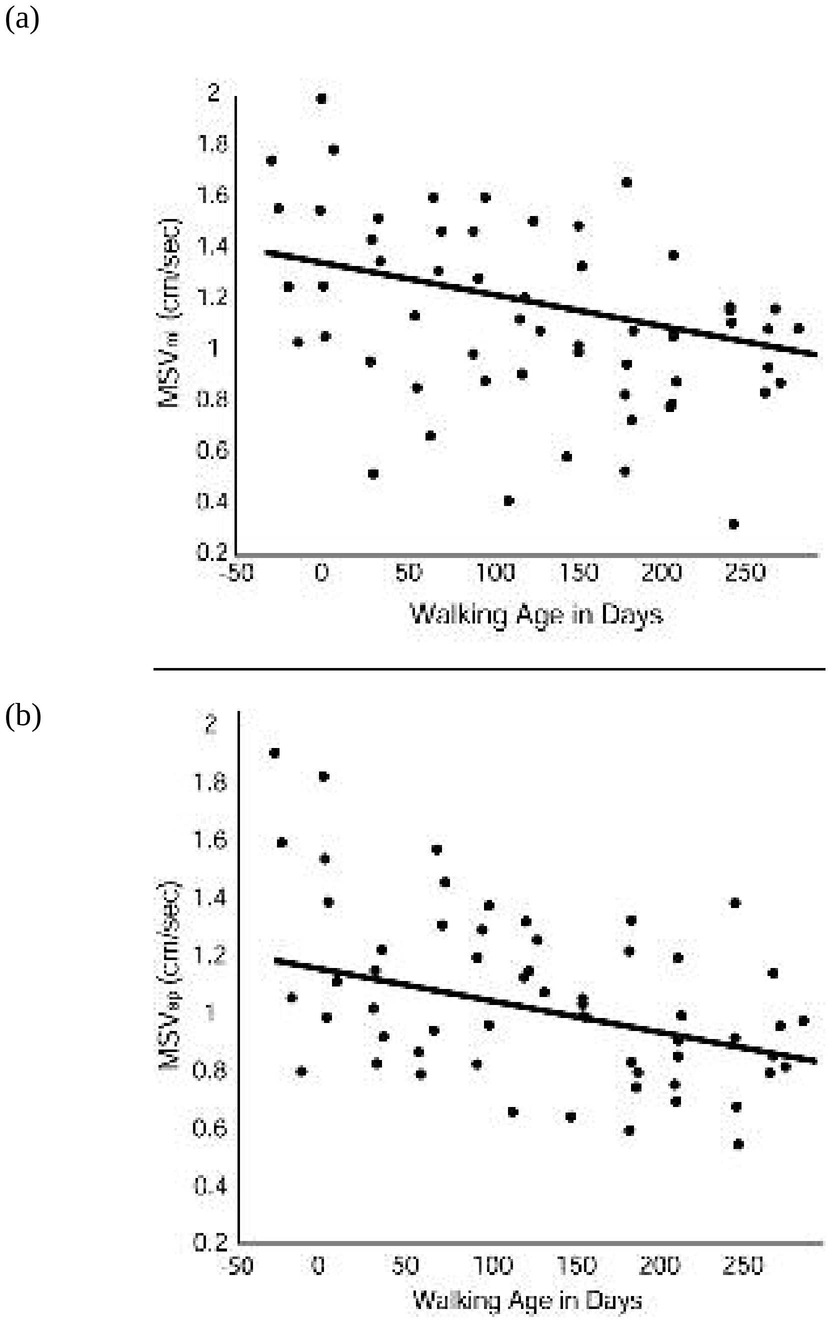


Figure 3. Mean Sway Velocity Across Walking Ages. (a) MSV$_{ml}$ and (b) MSV$_{ap}$ from the regression model across walking ages

Cross-Correlation of Postural Sway and TF_v.

To understand the relationship between postural sway and TF_v, the cross-correlation analysis was applied on TF_v with six sets of postural responses: 2 x 3 (position/velocity x COM_{ml}/COM_{ap} /COM_{rd}) respectively.

Position. The regression results indicated that only the coefficient (C) between TF_v and COM_{rd} had significant age effects. The full regression model was progressively reduced to a final polynomial model illustrated in Figure 4. This model adequately described and predicted the maximum correlation coefficient of the radial distance with TF_v across age and is as follows:

$$C = 0.03307 + 0.000326*A \qquad (3)$$

In this model, only the coefficient for the age term was significant ($p < .05$) but not the intercept. No age effects were observed for the either COM_{ap} or COM_{ml} maximum correlation coefficients, although the mean correlation coefficient was significantly different ($p < 0.05$) from zero for COM_{ap}. For three directions of position, there were no effects observed for corresponding time lags.

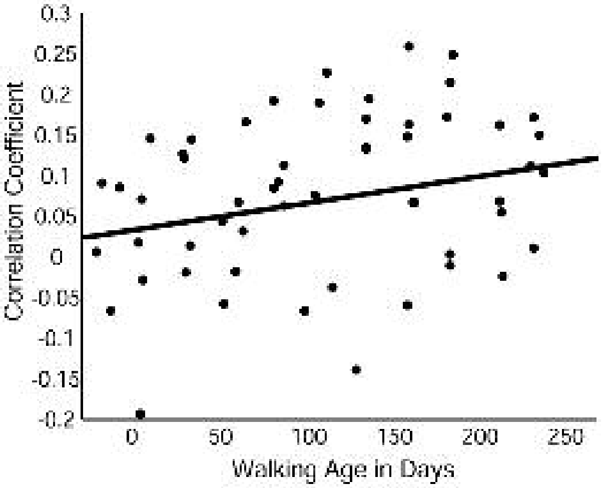


Figure 4. Maximum Coefficients between TF_v and COM position in radial distance from the regression model across walking age

Velocity. Analyses of the maximum correlation coefficients and the corresponding time lags for the cross-correlation of COM velocity (COM_{ml}, $COM_{ap,}$ and COM_{rd}) with TF_v revealed no age effects for either direction maximum correlation coefficients, although the mean correlation coefficient was significantly different ($p < 0.05$) from zero for COM_{rd} and COM_{ml}. No effects were observed for corresponding time lags for three directions of velocity.

Region-related NTF_v.

Position. Longitudinal changes in normalized vertical touch force (NTF_v) were examined in terms of walking age (A) and position ellipse (E_p). The final polynomial regression model (See Figure 5) was observed to be as follows:

$$NTF_v = 0.3534 + 0.000075*A + 0.02429*E_p - 0.00510*E_p^2 + 0.000321*E_p^3 - 0.00009*AE_p + 0.0000011*AE_p^2 \qquad (4)$$

The intercept and all of the coefficients, with the exception of the coefficient of age, were significant ($p < .05$). Planned comparisons for an interaction effect using Tukey's LSD revealed the following. Significant differences ($p < .05$) between ellipse 1 and 10 were observed across days 30, 90, 150, 210 and 270 but not across day -30. For ellipses 3 vs. 8 differences were observed across days 150, 210, 270, but not across days -30, 30, and 90. Significant differences ($p < .05$) between days -30 and 270, 30 vs. 210, and 90 vs.150 were observed for ellipse 10 and not for ellipses 1, 3 and 8. Table 1 represents the results of these comparisons.

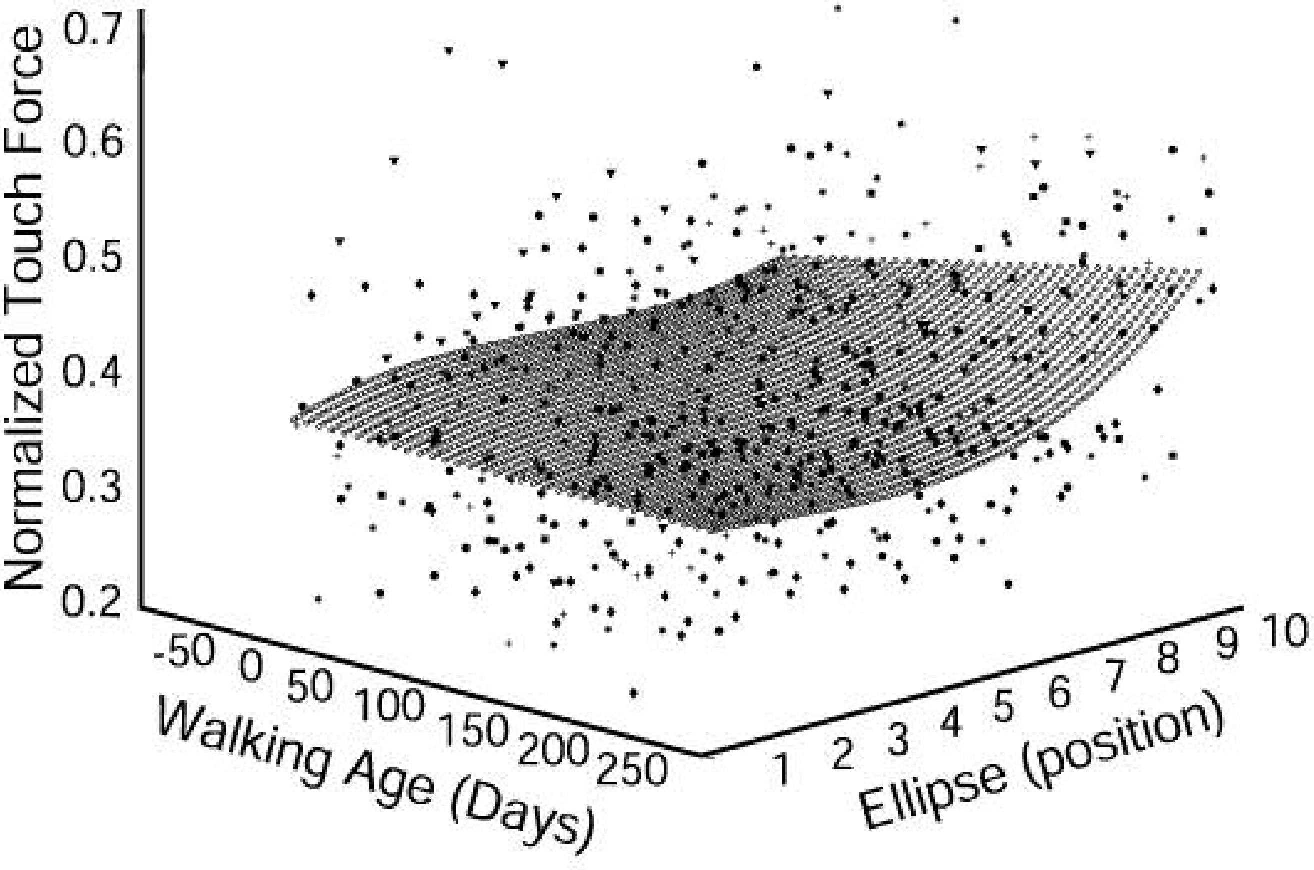
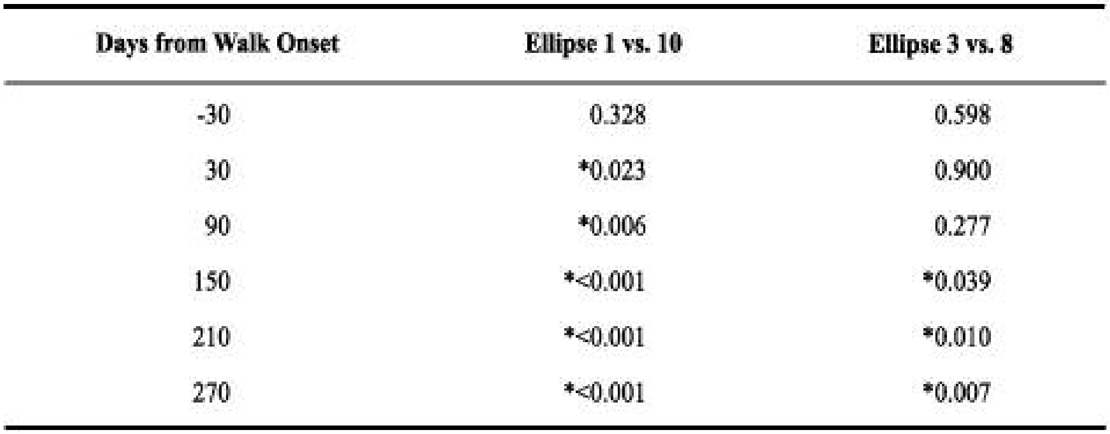


Figure 5. NTF$_v$ from Regression Model with Age, Position Ellipse and Interaction Effects.



Days from Walk Onset	Ellipse 1 vs. 10	Ellipse 3 vs. 8
-30	0.328	0.598
30	*0.023	0.900
90	*0.006	0.277
150	*<0.001	*0.039
210	*<0.001	*0.010
270	*<0.001	*0.007

Table 1. Planned Comparisons Summary. Results of the statistical analyses of planned comparison between position ellipses at predetermined time steps.
* Denotes a significant *p* value.

Velocity. The linear mixed regression analysis with correlated measures was also applied to examine the longitudinal changes in NTF_v in terms of age (A) and velocity ellipse (E_v). The final regression model was achieved (see Figure 6). There were no significant age related terms left in the final regression model for NTF_v, which was observed to be as follows:

$$NTF_v = 0.3574 + 0.01571*E_v - 0.00277*E_v^2 + 0.000183*E_v^3 \qquad (5)$$

All the coefficients were significant in this model ($p < .05$). Planned comparisons for the ellipse main effect by using Turkey's LSD showed that there were significant differences between both ellipses 1 and 10 and ellipses 3 and 8 ($p < .05$).

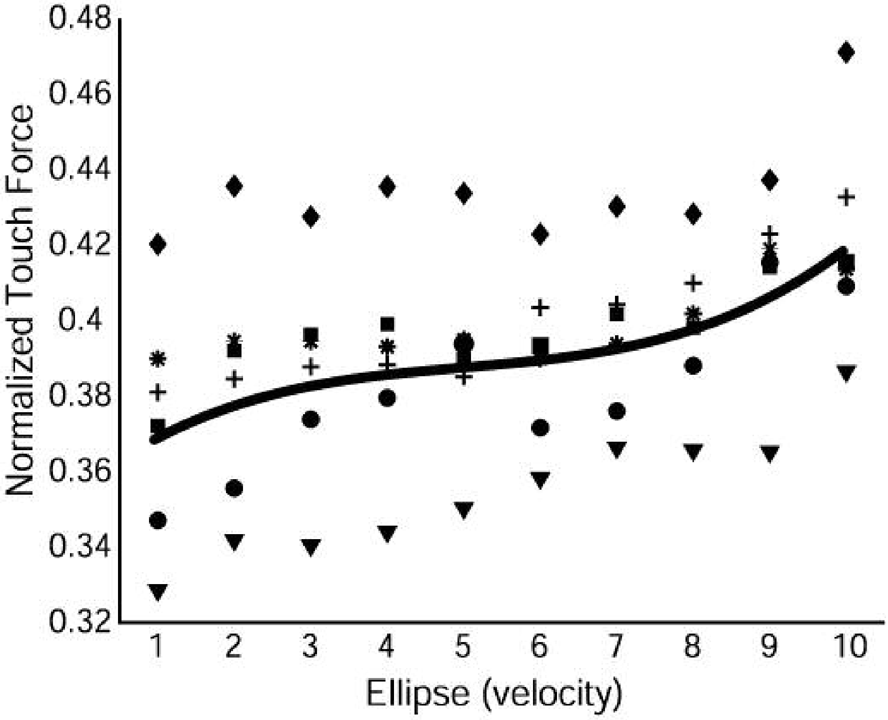


Figure 6. NTF_v from Regression Model for the Velocity Ellipse (The shapes represent individual subjects)

DISCUSSION

The current study has demonstrated that the amount of TF_v infants apply is dependent on their postural state. While maintaining stance with one hand in contact with a surface, infants applied more vertical TF_v when their body position was farther away from the center position and when their sway velocity was higher. This relationship between TF_v and body state arose coincidently with the development of upright stance. That is, infants with more walking experience applied nearly 40% more TF_v when their body position was in the outer fifth region than when it was in the inner fifth region of sway. However, the young infants with less walking experience applied the same TF_v across all sway regions. These findings are consistent with our general and developmental hypotheses. That is, in general, infants apply a strategy wherein hand use is dependent on perceived postural state. Developmentally, infants with the increased experience of upright stance better estimate their own stability, which leads to a more accurate application of the touch force.

Hand use for the maintenance of upright stance for newly walking infants is not reflexive but rather is adaptive to specific situations (Stoffregen et al., 1997). In a cross-sectional study, Stoffregen and his colleagues found that newly walking infants use their hand to hold onto something if their bodies are unstable (under relatively unstable surface condition) but remain hands-free if their bodies are stable. Our study supports and extends these findings by examining continuous TF_v as infants stood quietly over an extended period of time. In our task, infants used more TF_v when their bodies were relative unstable (i.e., nearing the boundary of their sway), even though their hands were in contact with the touch surface during the entire trial. Our findings extend Stoffregen's argument that hand use is not only dependent on the general postural task, but also is adaptive within a situation where touch contact is continuously maintained.

Across development, the use of the hand in the control of upright stance has been shown to change (Barela et al., 1999). In their longitudinal study, the authors found that the amount of ATF_v infants applied during quiet stance only differed between the PS (pull to stand) stage and the following three advanced developmental periods which did not differ from each other. Consistent with this finding, we observed that the amount of ATF_v infants applied remained at approximately 3.8 N from 1 month prior to 9 months post walk onset; ages which span the second (stand alone), third (walk onset), and fourth (post-walking) developmental periods in Barela and colleagues' study. Even though

ATF_v remained constant in these ages, the observed changes in the NTF_v across the ten sway regions suggests that the role of hand use for young infants is crucial in maintaining upright stance and supports the argument that young infants use postural strategies that incorporate the stability and control provided through the upper body (Sveistrup et al., 1996; Woollacott et al., 1992). Our results support the position that even after the trunk and lower limb control has been developed sufficiently for infants to maintain upright stance, hand use remains an adaptive mechanism that works as a function of body stability.

The apparent adaptiveness of hand use may be a response to the dual roles of the hand in upright stance control. That is, the hand may be used both for mechanical support and as a source of information. This point was demonstrated in Barela and colleague's longitudinal study (1999), wherein the authors observed virtually no time differences between medial-lateral TF (TF_{ml}) and medial-lateral postural sway for infants in the pull-to-stand, stand-alone, and walk onset developmental stages. However, TF_{ml} was shown to lead postural sway in the post-walking stage. The authors argued that infants with more walking experience had developed ability to use touch as a source of somatosensory information in controlling upright stance. Using a similar paradigm as Barela et al (1999), our results were not consistent with the previous findings, as we observed no meaningful time differences between vertical TF (TF_v) and postural sway in the infants with walking experience. A difference between the two studies was the use of TF_v in the present study compared to TF_{ml} and anterior-posterior TF (TF_{ap}) (Barela et al., 1999). TF_v can be assumed to be associated with both TF_{ml} and TF_{ap} due to the forces of friction. Here we have chosen TF_v as a global indicator of hand use. The increases in correlation between

TF_v and the radial distance of postural sway with age and the relationship between NTF_v and sway region and age both support our claim. As it is difficult to tease apart the TFs used for mechanical support and sensory information, future studies may use both methodologies to assess this issue. That is, directional touch forces may be more sensitive in terms of timing issues (Barela et at, 1999) and TF_v may be more sensitive to detecting more global changes in the hand use.

Further insights into the dual roles of the hand may be gained by examining the non-linearity of the relationship between TF_v and postural sway. Specifically, the region related analyses indicated that, in general, TF_v was applied non-linearly across sway regions with the majority of forces being applied when sway was furthest from the center. The observed non-linearity between TF_v and position (and velocity to a large extent) supports the argument that the infants used their hand primarily for mechanical support only during specific aspects of sway. For the more experienced infants, this interpretation would allow for the hand to be used for other purposes the majority of the time, which is consistent with findings that suggest that post-walking infants use touch primarily as a source of information for the attenuation and exploration of postural sway (Metcalfe et al., 2001). Taken together, the aforementioned studies suggest that infants apply a non-linear touch strategy that simultaneously allows for both mechanical support and sensory detection.

The infants may use such a touch strategy to offset their postural instability. The instability of newly walking infants has been demonstrated in several studies. For example, infants are more susceptible to visual perturbations (Lee & Aronson, 1973) and have less refined automatic postural responses (Sveistrup et al., 1996) compared to adults. We have shown in a previous paper that infants have greater sway amplitude than adults even though the infants' bases of support are substantially smaller (McDowell et al., 2003). Similar results are suggested for velocity by comparing our present results with those in adults (Prieto et al., 1996). Although sway amplitude and velocity do not necessarily reflect stability, the observation that the proportions between the infants' postural sway variables and their base of support are much larger relative to that of adults. This observation suggests that newly walking infants are highly unstable. This supports the assumption that decreasing sway amplitude and velocity indicate increasing stability in the present task. Our data thus support the findings that the postural sway of newly walking infants is highly unstable.

The infants can address their instability either by using a strategy that allows for a large sway variance or by reducing the sway variance. It appears that the infants first use a strategy that maintains a large sway variance. That is, the velocity-based touch strategy that the infants use from the time before walk onset and the position-based touch strategy that appears during the few months following walk onset suggest the use of mechanical support during times when the infants are more likely to fall. This general strategy allows the infants to sway more and to catch themselves when they are off-balance. The present data suggest that reductions in the amount of postural sway occur after the infant has learned to effectively use the touch strategy. That is, no evidence is presented suggesting that these young infants decrease their MSA and the decreases observed in MSV occur after walk onset, a time period during which the velocity-based touch strategy appears to already been used effectively. These results thus support the use of a touch strategy as an important component to the development of upright stance.

In attempting to fully assess sway stability, interesting differences were observed between the TF relationship with sway position and the TF relationship with sway velocity. That is, we observed an age by ellipse interaction for position but only an ellipse main effect for velocity. The findings for region-related NTF_v in velocity hint that velocity of postural sway is a crucial factor for controlling upright stance in the early development of upright postural control. Young infants around walking onset already have the ability to detect velocity differences and apply more TF_v when they have higher sway velocity. Further, the decrease in MSV across walking age precedes potential decreases in MSA. The importance of velocity information contributions to upright postural control has also been supported in several adult postural studies, which have reported that some postural reactions were adapted to velocity information (Jeka, Ribeiro, Oie, & Lackner, 1998; Masanil, Popovic, Nakazawa, Kouzaki, & Nozaki, 2003; Morasso & Schieppati, 1999; van Wegen et al., 2002). While our findings suggest the early control of velocity in development of upright postural control, the issue of the relative development of position versus velocity based control needs to be examined in further studies.

In conclusion, our study demonstrated that infants' hand use changes with walking experience. However, these changes are consistent with our hypothesis that infants more effectively apply a single touch strategy with increase walking experience. That is, with increased walking experience, infants more accurately detect their postural state. Their better state estimation allows for greater mechanical forces to be applied when the infant is unstable, thus more effectively retuning the infants' stability.

CHAPTER 4

FUTURE STUDIES

In our current study, we found that the infants' application of hand force depended on their current postural state. With development, infants appeared to better estimate their postural state, which led to a more efficient application of the touch strategy used to maintain their upright stance. In this last chapter, we discuss further studies on hand use in upright stance, which may contribute to our knowledge of the development of upright postural control.

Muscle Response of Upper Limbs in Development of Upright Postural Control.

In the current study, to understand how infants use their hand in upright stance, we used several analyses to examine the relationship between hand touch and postural sway. Although the measures we used (such as region-related touch force) provided an initial understanding of hand use, future studies could incorporate actual muscular responses, more precise motions of the upper limb, or both in combination to extend the knowledge of how infants use their hands to respond to changes in the movement of their bodies.

Our initial study examined how infants use their hand during quiet unperturbed stance, which was designed to answer how infants use their hand in general. It may be also be of interested to examine how infants use their hand in more dynamic environments (e.g. an oscillating support surface or discrete platform perturbations). Several adult studies have addressed the issue of muscular responses of upper limbs in respond of instable posture after a platform perturbation (Cordo et al., 1982; Maki et al., 1997).These studies found that the activation and pattern of muscles of upper arm are similar to those of the leg, however, the development of this muscular response is unexplored. Therefore, the examination of muscular response of arm after perturbations would extend our initial finding regarding the hand strategies that infants apply and the changes of those strategies with development.

Dual Role of Hand Use in Upright Postural Control.

To examine the dual role of hand use in upright postural control, cross correlation analysis was utilized in our study to detect potential time lags between forces and postural responses. However, we found no significant time lag changes across ages. This result was not consistent with the previous findings found of Barela et al. (1999) However, there are slight methodological differences in examining the TF data in these two studies. In our study, we only recorded vertical TF as a global measure studied its relationship to the medial-lateral and anterior-posterior sway. Barela et al. recorded the three directions of TF data and studied their relationship to the corresponding directions of the postural sway. Considering the different results in the two studies, we conclude that directional touch forces may be more sensitive in terms of timing issues and vertical TF may be more sensitive to detecting more global changes in the hand use. Therefore, future studies may benefit by including both methodologies to help fully understand the role of hand use in upright postural control.

Further Ideas

Defining stability in postural sway is difficult. In our present study, we used both position and velocity to define a “relative stability” terms. Our findings suggested that velocity-based control seems to develop early while position-based control develop later with more walking experience. While there is evidence of differences in position and velocity based-control, other measures that incorporate both position and velocity together (e.g. time to boundary) may help to further understand the concept of stability in the development of postural control.

Finally, the region-related vertical NTF analyses yielded a significant aging effect in the newly walking infants. It would provide insight into hand use strategies to examine this same analysis across the complete range of development (i.e., from newly sitting infants to the elderly).

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APPENDIX A

Alternative Analysis

Alternative Analysis

This section includes two analyses, which were included in the thesis proposal. However, as is discussed below, these two analyses provided similar information as those analyses currently included in Chapter 3. The first analysis, the between-trial correlations, was originally included in this thesis to demonstrate the general relationship between vertical TF and postural sway. The results of this analysis suggested the existence of the general relationship that was pursued in detail by the region-related TF analysis. The second analysis, event-related analysis, was designed to examine the temporal relationship between TF and postural sway. However, insufficient data in our study made this analysis difficult to apply and the results of this analysis confirmed the region-related TF analysis, but did not provide any additional information of value to the thesis. For clarity, these redundant analyses are not included in the body of this thesis, yet they appear here for completeness. Included below are the method, results, and discussion of these two analyses.

1. Between Trial Correlations between TF_v and postural sway.

Methods.

Between trial correlations of (1) mean absolute TF_v and mean sway amplitude (MSA) and (2) mean absolute TF_v and mean sway velocity (MSV) were computed across trials. Both MSA and MSV were calculated for two directions of COM - medial-lateral (COM_{ml}) and anterior-posterior (COM_{ap}). MSA was defined by calculating the standard deviation of the postural time series data. MSV was defined by calculation of the total excursion of postural sway divided by the duration of the trial. A simple linear regression was applied to examine the relationship between TF_v and MSA/ TF_v and MSV.

Results.

For the correlation of TF_v and body position, a significant positive relationship of TF_v and MSA in COM_{ml} was found (F (1,32) = 6.337; $p < 0.05$, $R^2 = 0.1697$), which indicates that as infants had higher sway amplitude in media lateral direction, they applied more touch force. Similarly, for correlation of TF_v and sway velocity, a significant positive relationship of TF_v and MSV in COM_{ml} was found (F (1,32) = 6.899, $p < 0.05$, $R^2 = 0.1820$). Figure 7. illustrates the regression results in TF_v and MSA.

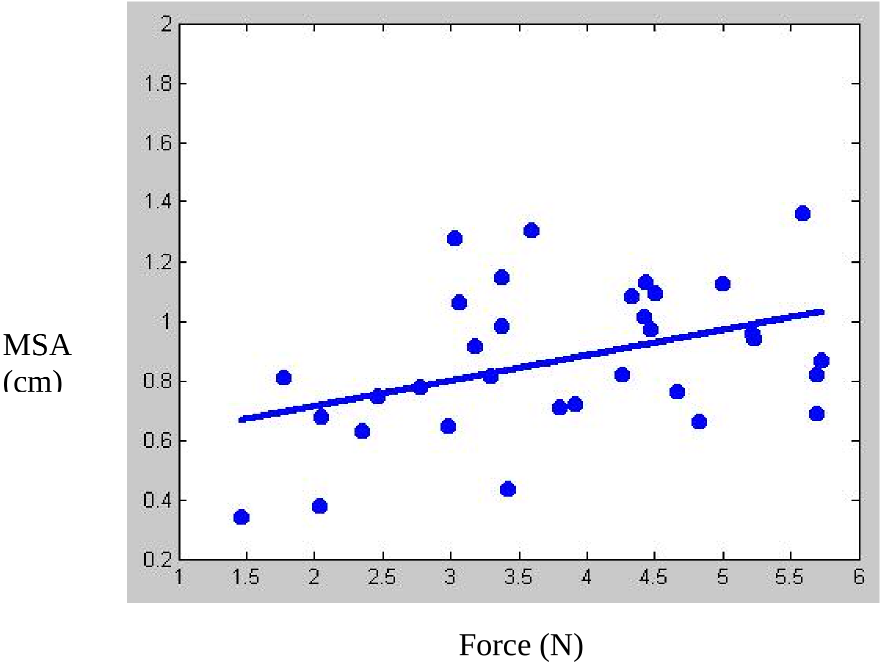


Figure 7. The regression result of TF_v and MSA in COM_{ml} ($p < 0.05$, $R^2 = 0.1697$)

2. Event-Related Analysis.

In order to examine the phase relationship between postural sway and TF_v in different regions of postural sway, an event-related analysis was applied. This analysis was designed to acquire temporal relationship between TF_v and postural sway nonlinearly, which would be associated with examination of the role of sensory use in upright postural control.

Methods.

Event-related methods are based on signal averaging across sections of data that are time-locked to a specific event. For the purpose of this analysis, events were defined as the peaks in the position and velocity signals. The peaks in position/velocity were identified as filtered postural data points (10th order Butterworth; $f_{3db} = 2$ Hz) with zero velocity and zero acceleration respectively. The time-locked NTF_v was computed by windowing the filtered NTF_v data +/- 3 sec from the events (peaks) in the postural data. The NTF_v corresponding to the peak within each position and velocity ellipses were averaged across epochs yielding averaged NTF_v from 3s prior to 3s post peaks in the postural data. The baseline for each epoch was calculated by averaging the NTF_v from the first and last s within each 6 s epoch. The peak NTF_v in each epoch was chosen by finding the maximum NTF_v subtracted from the baseline (called Amplitude). Amplitude of the peak was recorded and analyzed across age and ellipse to examine the amplitude change in NTF_v peaks.

Time lag between postural sway and NTF_v was calculated as the time of the peak of the time-locked NTF_v relative to the time of the peakin the postural data. To confirm that the peak of the time-locked NTF_v actually represents a peak, the amplitude of peak the difference between the values of peak NTF_v and the average NTF_v was calculated and only the value larger .05 were chosen as NTF_v peak in an epoch. Considering that this analysis requires many samples to increase the signal to noise ration, the analysis used only 5 ellipses (each containing 20% of the data).

Results.

Amplitude

Position. The longitudinal change in amplitude of peak in NTF_v in terms of walking age (A) and position ellipse (E) was examined by applying the linear mixed regression analysis with correlated measures. The AR1 covariance method was applied to account for the correlated measures and the final regression model (Figure 8) was observed to be as follow:

$$\text{Amplitude} = 0.04481 - 0.00015*A + 7.363E\text{-}7*A^2 - 0.01735*E + 0.004240*E^2 \tag{7}$$

The intercept and all of the coefficients are significant ($p < .05$), with the exception for the coefficient of linear ellipse term ($p = 0.06$).

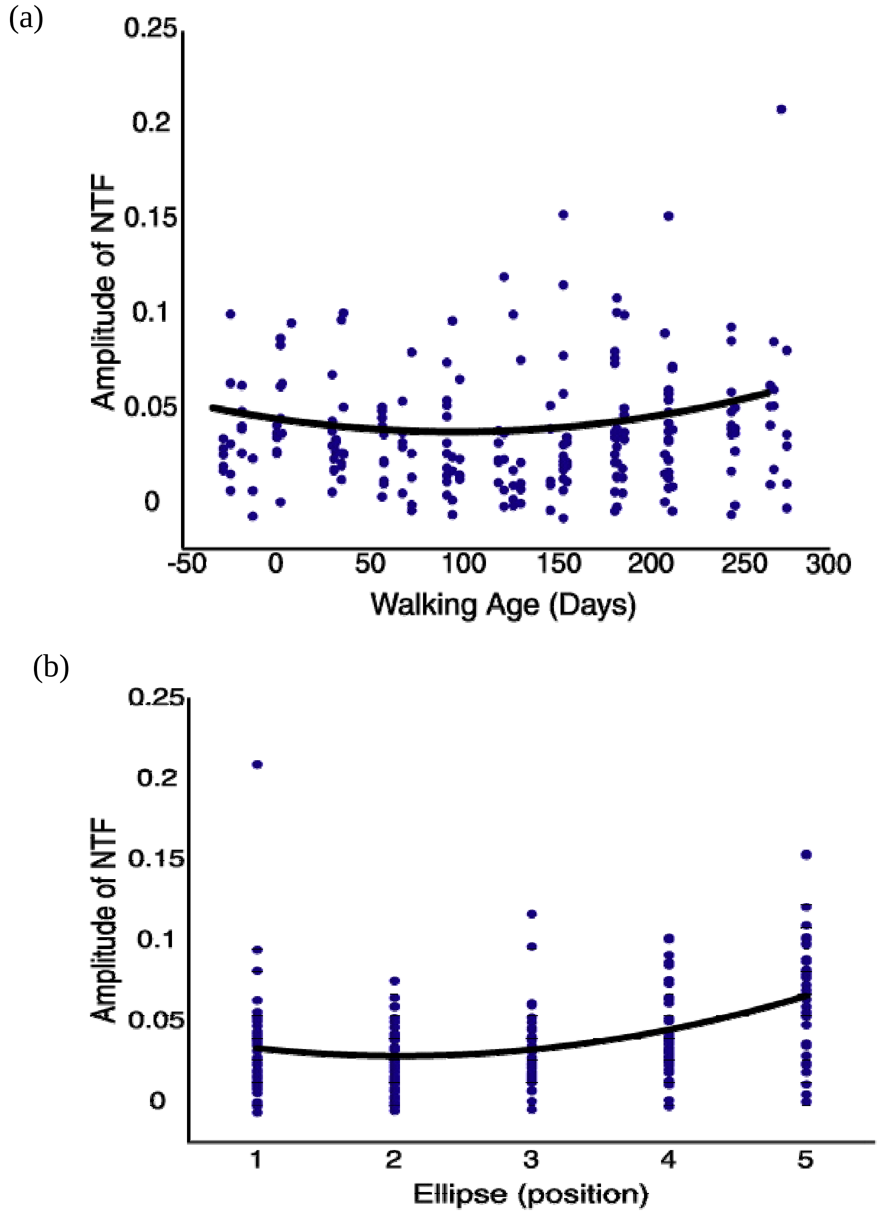


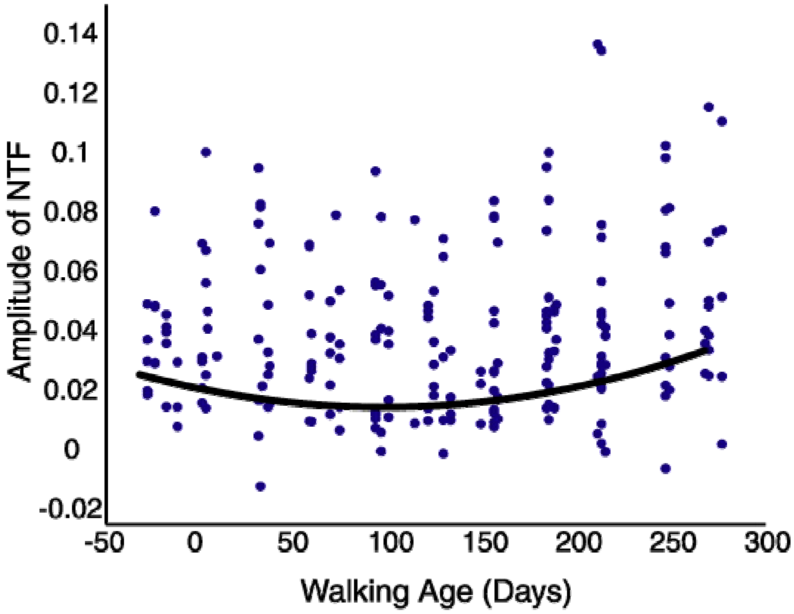
Figure 8. Amplitude from regression model with (a) age effect (b) ellipse effect

Velocity. The linear mixed regression analysis with correlated measures was also applied to examine the longitudinal change in amplitude of peak in NTF_v in terms of walking age (A) and velocity ellipse (Ev). The AR1 covariance method was applied for the correlated measures. The final regression model for Amplitude (See Figure 9) is as follow:

$$\text{Amplitude} = 0.01952 - 0.00013*A + 6.529E\text{-}7*A^2 - 0.00167*Ev + 0.002550*Ev^2 \qquad (8)$$

The intercept and all of coefficients were significant ($p < .05$) except the linear ellipse term ($p = 0.7$).

(a)



(b)

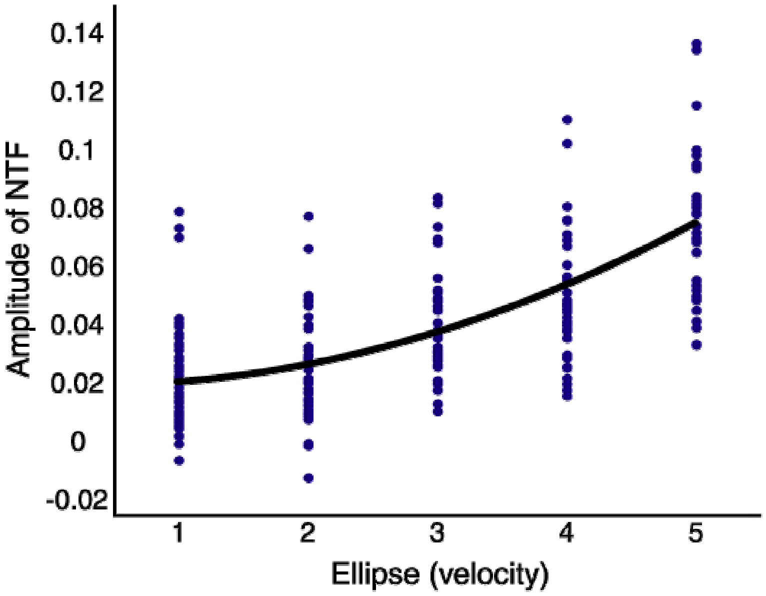


Figure 9. Amplitude from regression model with (a) age effect and (b) ellipse effect

Time Lag

<u>Position.</u> For the time lag analysis, time lag was chosen only when the amplitude of position and/or velocity event-related analysis was larger than 2*SD of the baseline of NTF$_v$ for each trial. Therefore, decreased sample size for this analysis was observed. By comparing the AICC fit statistic in SAS program, the linear mixed model analysis is a better method to fit data than the regression analysis. As a result, a linear mixed model with three fixed sources of variance age (11 levels), ellipse (5 levels) and age by ellipse interactions was applied. CS covariance structure was used to account for the correlated measures. The results for this analysis showed that there

was no significant age and ellipse main effects and interaction effect found for Time Lag.

Velocity. The linear mixed model with variance covariance techniques was also applied to examine age, velocity ellipse and interaction effects on Time Lag. AR(1) covariance structure was applied to account for the correlated measures. There was no significant age and ellipse main effects and interaction effect found.

Discussion

The between-trial correlation and event related analyses were not included in the main text of this thesis primarily because they did not add to the understanding of how infants their hand touch in upright stance. The results of between-trial correlation indicated a positive relationship between TF_v and postural sway, which suggested the need of another more extended analysis: region-related TF_v. The results of region-related TF_v support the findings from between-trial correlation, while considering age effects and individual participants in addition to the moment-to-moment relationship between TF_v and postural sway. Therefore, the between-trial correlations were not needed in the main text as they provided no new information.

The purpose of the event related analysis was to examine the phase relationship between TF and postural sway. Therefore, we were specifically interested in time lag portion of the analysis. However, the results of time lag were not significant. Moreover, there were several difficulties in this analysis. First, the event-related amplitude was examined to support the region-related TF analysis, which it did, and also to validate time lag. However, this procedure of validating time lag resulted in few data left which were unevenly distributed across subjects and ellipse. Furthermore, these data had high variance relative to the expected difference. Due to theses reasons, we think it is unworthy to report the event-related analysis in the thesis.

APPENDIX B

Participant Consent Form

Participant Consent Form

Project	Postural development and perception-action coupling.
Statement of Subject's Age	I state that I am over 18 years of age and that I allow my infant to participate in a program of research being conducted by Jane E. Clark at the University of Maryland, Department of Kinesiology.
Purpose	I understand that this research study will examine how infants at different developmental periods use surface contact while sitting and standing upright.
Procedure	The procedure involves monthly visits to the Motor Behavior Lab of 40-60 minutes each for the first 4-5 months and bimonthly visits for the next 8-9 months. The visits will take place over a period of about one year to one year and two months as your infant progresses from sitting to three months of walking experience. Bimonthly visits will begin once your infant begins standing and will be scheduled within five days of each other. Your infant will sit in a modified infant seat or stand on a small wooden pedestal (20 X 10 X 3.5 cm) without touch support or touching a rounded surface with the right hand. The touch surface, the seat and the standing pedestal contain instruments that measure the force the infant applies to them. Small, light-weight plastic triangles attached to a waistband and headband will be placed on the infant's lower back and head. The triangles are instruments to measure the body's movement. There will be 17-22 trials per testing session depending upon the postural development of the infant (i.e. sitting or standing). Each trial will be 30 seconds. The infant will also be videotaped during data collection.
Risks	Any possible risk to my infant is minimal. I understand that my infant may lose control of his/her upright posture. Prompt assistance will be provided by either the parent and/or experimenter who will be standing next to my infant. There are no other known risks and no long-term effects associated with this study.
Confidentiality	I understand that all information collected in this study is confidential and that my infant's name will not be identified at any time during reports and presentations. All information will be coded and stored in a locked cabinet.

Benefits:	I understand that the experiment is not designed to clinically test or treat my infant or to help the infant personally. This investigation seeks to learn more about the postural control of infants.
Freedom to Withdraw and Ask Questions	I understand that I am free to ask questions or to withdraw my child from participation at any time without penalty. I understand that I must have a signed copy of this consent form given to me and that the investigators will provide me with the results from this study.
Principal Investigator	Jane E. Clark, Ph.D. 2351 Health and Human Performance Building University of Maryland Lab Phone: (301) 405-2574 College Park, MD 20742-2611 Office Phone: (301) 405-2450

_______________________________ ____________
Name of Infant Birthday

_______________________________ ____________
Signature of Parent or Legal Guardian Date

APPENDIX C

Summary of Data Spreadsheets

Descriptive Variables

Subject 1

Walking Age (Days)	ATF	MSA_{ml}	MSA_{ap}	MSV_{ml}	MSV_{ap}
-24	4.2682	0.8202	0.9051	1.5591	1.6202
4	2.7855	0.7784	0.9220	1.0564	1.4160
32	4.3319	1.0801	0.7842	1.4387	1.1785
67	3.4271	0.4354	0.7144	0.6671	0.9699
93	5.0010	1.1223	0.7710	1.4697	1.2227
121	NA	0.8812	0.8457	1.1250	1.1538
156	NA	0.7222	0.9221	0.9965	1.0612
184	4.6737	0.7592	0.9146	0.8296	1.2444
213	2.4648	0.7437	0.6007	1.0815	0.9353
248	4.8291	0.6630	0.4450	1.1124	0.7059
274	3.2969	0.8116	0.8694	1.1661	0.9838

Subject 2

Walking Age (Days)	ATF	MSA_{ml}	MSA_{ap}	MSV_{ml}	MSV_{ap}
-12	NA	0.7052	0.4897	1.0344	0.8269
9	5.2257	0.9571	0.6213	1.7892	1.1385
37	3.1855	0.9143	0.4241	1.3521	0.9472
58	5.6932	0.8195	0.6364	1.1383	0.8944
93	4.5078	1.0913	0.7629	0.9901	0.8529
122	NA	0.4272	0.8183	0.9098	1.3465
156	3.0711	1.0584	0.7434	1.4915	1.0809
185	NA	1.4798	0.9696	1.6617	1.3514
213	4.4420	1.1294	1.0698	1.0578	0.8799
247	NA	0.7423	0.8849	1.1756	1.4109
268	2.9830	0.6470	0.5884	0.8381	0.8224

Subject 3

Walking Age (Days)	ATF	MSA_{ml}	MSA_{ap}	MSV_{ml}	MSV_{ap}
33	2.0413	0.3753	0.5902	0.5205	0.8547
72	NA	0.8991	0.9456	1.3143	1.3348
114	NA	0.2124	0.5984	0.4148	0.6875
149	NA	0.6262	0.6230	0.5862	0.6708
184	2.0535	0.6786	0.5678	0.5308	0.6241
211	NA	0.7512	0.7030	0.7820	0.7818
249	1.4676	0.3377	0.6482	0.3225	0.5739
270	2.3562	0.6277	0.8182	1.0858	1.1679

Subject 4

Walking Age (Days)	ATF	MSA_{ml}	MSA_{ap}	MSV_{ml}	MSV_{ap}
2	NA	1.1190	0.7209	1.9902	1.5635
36	NA	1.0698	0.6389	1.5201	1.2488
69	4.4255	1.0145	0.8577	1.6014	1.5976
100	5.5876	1.3621	0.8898	1.6025	1.4024
133	5.6897	0.6869	0.7776	1.0799	1.1017
156	3.9166	0.7175	0.6484	1.0228	1.0187
189	NA	0.7547	0.7659	1.0809	0.8247
212	NA	0.5934	0.5034	0.7935	0.7238
288	NA	1.0838	0.7000	1.0878	1.0034

Subject 5

Walking Age (Days)	ATF	MSA_{ml}	MSA_{ap}	MSV_{ml}	MSV_{ap}
-18	NA	0.5819	0.5714	1.2534	1.0824
3	NA	0.7016	0.6801	1.2557	1.0148
31	NA	0.5159	0.6169	0.9598	1.0459
59	NA	0.4600	0.4113	0.8572	0.8176
100	NA	0.5260	0.6028	0.8834	0.9886
129	5.2369	0.9403	1.1407	1.5094	1.2827
158	3.6011	1.3052	0.6823	1.3316	1.0157
185	NA	0.7026	0.5218	0.9490	0.8595
213	3.0365	1.2744	0.9745	1.3753	1.2215
247	NA	1.0503	0.6971	1.1611	0.9434
277	NA	0.6718	0.5442	0.8766	0.8441

Subject 6

Walking Age (Days)	ATF	MSA_{ml}	MSA_{ap}	MSV_{ml}	MSV_{ap}
-28	NA	0.9221	1.0213	1.7479	1.9328
1	NA	0.9291	1.0025	1.5520	1.8515
74	3.3742	1.1451	0.9174	1.4703	1.4831
96	1.7795	0.8101	0.6839	1.2851	1.3187
124	3.3741	0.9812	0.9602	1.2101	1.1759
188	3.8064	0.7068	0.5384	0.7292	0.7722
215	4.4684	0.9724	0.7088	0.8809	1.0208
270	5.7338	0.8654	0.5679	0.9365	0.8813

Cross-Correlation
Maximum Coefficient

Subject 1	**Position**			**Velocity**		
Walking Age (Days)	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF
-24	-0.0458	0.3267	0.0901	0.1035	0.2332	0.1431
4	0.0684	0.0102	-0.0291	-0.0708	-0.0803	-0.0345
32	-0.4286	0.1559	0.1208	0.2307	0.2633	0.2237
67	0.3882	0.1039	-0.0185	-0.2742	-0.2839	-0.2454
93	0.1152	0.1053	0.0841	0.0959	-0.0410	0.0759
121	0.2538	0.2017	0.0755	0.1431	-0.0600	0.1038
156	-0.1109	0.1171	0.1692	-0.0417	-0.0313	0.2284
184	-0.2273	-0.1220	-0.0601	-0.0850	0.1299	0.0987
213	-0.3877	0.1992	-0.0113	0.1505	0.0570	0.1863
248	0.8473	0.5632	0.0542	-0.3310	0.2428	0.4995
274	-0.0684	0.0445	0.1493	0.0463	0.0241	0.1920

Subject 2	**Position**			**Velocity**		
Walking Age (Days)	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF
-12	0.2067	0.0478	0.0851	-0.1658	-0.0167	0.3531
9	0.4370	0.1471	0.1450	0.0531	-0.1722	0.2153
37	-0.2592	0.1510	0.1440	-0.1644	0.0831	0.0542
58	0.4278	0.1349	0.0437	0.0374	0.0099	-0.0009
93	0.0288	0.4456	0.1913	0.0276	-0.0539	0.2407
156	0.1732	0.1246	0.1339	-0.0398	-0.0054	0.3480
185	0.1331	-0.2879	0.1622	-0.0356	0.0372	0.1994
213	-0.2017	0.4776	0.0023	0.0182	0.0484	0.1020
247	0.3905	0.5497	0.0675	-0.0284	-0.0556	0.0019
268	0.0011	-0.1266	0.1112	0.0466	0.1528	0.3460

Subject 3	**Position**			**Velocity**		
Walking Age (Days)	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF
33	0.0805	-0.3493	-0.0198	0.3306	0.1839	0.0042
72	0.0074	0.2507	0.0309	0.1774	0.3660	0.0649
114	-0.2863	-0.1714	-0.0670	0.0172	-0.2153	0.1486
149	0.3060	-0.2264	-0.1396	0.1099	-0.1738	0.1410
184	-0.3727	0.1214	0.1474	0.0295	0.2053	0.2474
211	0.4158	0.5108	0.1715	0.2645	0.0665	0.2788
249	0.1742	0.0339	-0.0243	0.0122	0.0986	0.2085
270	-0.5259	0.2660	0.0104	0.2716	-0.3139	-0.0128

Subject 4	**Position**			**Velocity**		
Walking Age (Days)	COM$_{ml}$/TF	COM$_{ap}$/TF	COM$_{rd}$/TF	COM$_{ml}$/TF	COM$_{ap}$/TF	COM$_{rd}$/TF
2	0.5982	0.4987	-0.1937	0.2712	-0.4508	0.1186
36	0.0808	0.1091	0.0132	-0.0425	-0.0156	-0.0711
69	-0.3096	-0.4752	0.0668	-0.0187	0.1985	0.1740
100	-0.1386	-0.2154	0.0621	0.3066	-0.0288	0.0934
133	-0.2985	-0.0843	-0.0379	0.0326	0.0413	-0.0272
156	-0.3380	-0.0731	0.1320	0.0740	0.0339	0.2619
189	-0.0476	0.2155	0.0662	0.0594	0.0130	-0.0524

Subject 5	**Position**			**Velocity**		
Walking Age (Days)	COM$_{ml}$/TF	COM$_{ap}$/TF	COM$_{rd}$/TF	COM$_{ml}$/TF	COM$_{ap}$/TF	COM$_{rd}$/TF
-18	0.3004	0.4617	-0.0668	-0.1005	-0.1288	-0.0204
3	0.1000	0.2180	0.0704	-0.0393	-0.1453	0.2550
31	0.2452	0.2411	0.1266	0.1858	0.2355	0.3032
59	-0.3640	-0.0320	-0.0584	-0.1065	0.1085	-0.0157
100	-0.1068	0.2626	0.1124	0.1646	-0.1148	0.2256
129	0.0974	-0.2045	0.2262	0.1477	0.0530	0.1446
158	-0.4269	0.1181	0.1939	0.0366	-0.1902	0.1951
185	-0.4898	0.2928	0.2582	0.0848	-0.0511	0.2727
213	0.1337	-0.4503	0.2141	0.0678	-0.1108	0.1444
247	-0.3321	-0.1704	0.1614	-0.0864	-0.0979	0.2861
277	-0.1532	0.0596	0.1027	0.0173	-0.0578	0.2271

Subject 6	**Position**			**Velocity**		
Walking Age (Days)	COM$_{ml}$/TF	COM$_{ap}$/TF	COM$_{rd}$/TF	COM$_{ml}$/TF	COM$_{ap}$/TF	COM$_{rd}$/TF
-28	0.0410	0.0783	0.0054	0.1854	0.2523	0.2048
1	-0.0975	0.1880	0.0170	0.1224	0.0286	0.1617
74	0.2143	0.1460	0.1655	0.1556	-0.0008	0.0742
96	-0.0872	-0.2690	0.0913	0.2472	0.0735	0.1779
124	0.3705	0.3956	0.1890	0.0400	0.0432	0.1717
188	0.0451	0.2257	0.0662	0.1759	0.0548	-0.0375
215	-0.5004	0.2166	0.2482	0.1410	0.2410	0.1836
270	-0.2640	0.4734	0.1708	0.0381	0.0012	0.1329

Cross-Correlation Time Lag (msec)

Subject 1	**Position**			**Velocity**		
Walking Age (Days)	COM$_{ml}$/TF	COM$_{ap}$/TF	COM$_{rd}$/TF	COM$_{ml}$/TF	COM$_{ap}$/TF	COM$_{rd}$/TF
-24	56.1912	154.4556	122.4559	-137.4110	-177.5526	-65.0765
4	297.2872	6.4686	-157.3887	7.3242	-143.6352	201.7738
32	-85.4609	10.5007	-266.2908	210.8845	-263.0206	225.2330
67	-258.5286	-19.4202	-516.5905	208.3808	-189.0504	437.0791

93	181.2062	97.3163	2.9201	70.3187	189.1049	198.2655
121	374.2786	-92.9641	-407.9317	137.7628	-44.2869	-78.3724
156	135.8741	-368.1747	-167.9752	-338.9601	-117.3131	-130.8628
184	132.5783	-116.3001	-185.0301	260.4774	-462.0792	476.8528
213	-154.8180	141.8708	-78.2704	181.9214	5.5582	-231.2344
248	-496.7216	0.0000	-516.5905	-158.9509	-139.0821	-178.8198
274	-407.7064	-101.7035	-87.9172	44.0958	170.9872	-255.7216

Subject 2	**Position**			**Velocity**		
Walking Age (Days)	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF
-12	-72.8089	-37.5548	-276.9485	55.6198	-279.6870	-24.1564
9	-191.4446	-121.9245	-239.9234	51.4727	220.0545	-344.0831
37	-218.5192	185.6364	112.2435	-474.9380	-168.8439	78.8308
58	114.4331	34.2480	240.2649	-122.0774	-252.6346	-25.1490
93	-345.3772	-199.1694	-325.0275	90.2298	119.1474	-516.5905
156	-55.6096	-400.3230	-282.3017	-141.1896	49.0932	-84.4948
185	-90.9811	-124.6721	-204.9734	-237.2366	329.8834	-201.6560
213	-66.4683	-8.3273	91.3002	24.6820	-307.0931	-139.3652
247	-18.6206	-4.1085	67.8550	40.9501	-49.8944	-80.1580
268	316.4774	-241.9902	197.2905	-71.3755	-126.5037	-39.2279

Subject 3	**Position**			**Velocity**		
Walking Age (Days)	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF
33	-48.4357	-384.1172	32.0417	65.7783	-67.1427	202.2062
72	313.3913	136.3081	-49.9766	52.1868	-112.4023	-210.6190
114	-161.1991	-268.1689	353.1281	88.7339	-470.7463	-323.5071
149	339.9616	476.8528	476.8528	179.3864	-132.2451	-351.1803
184	212.2104	-110.9511	-23.1661	-210.9486	-309.7096	30.6641
211	244.8059	-87.1747	227.3574	83.4972	-82.4018	244.1382
249	-196.4286	32.2108	224.7088	-442.6375	103.7367	-289.4251
270	-173.8716	94.8330	-402.7624	342.9374	343.5927	322.8501

Subject 4	**Position**			**Velocity**		
Walking Age (Days)	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF
2	99.3443	-119.2132	476.8528	-516.5905	278.1641	-516.5905
36	98.3678	277.2823	-109.5378	-471.4521	-272.1905	-273.7549
69	-31.6833	-97.9526	46.3043	-113.3387	42.4635	7.1279
100	-214.2220	-140.5066	15.1618	90.7477	-56.5346	57.7114
133	-107.3956	139.4763	129.1009	-203.5988	-127.1971	-31.7850
156	-48.1418	-280.6206	15.3177	-170.6219	98.1034	288.0841
189	-341.4451	-161.5688	-105.6366	-108.9882	179.4596	-149.7766

Subject 5	**Position**			**Velocity**		
Walking Age (Days)	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF
-18	18.5641	-90.3644	-392.0358	239.3239	217.3666	-237.8397
3	31.9059	-282.8261	-21.8132	-124.7705	150.9880	41.3023
31	357.7534	-34.6346	-2.9721	63.9889	-242.2016	270.2944
59	-42.6313	-324.8704	-368.0873	-256.8795	-180.0323	-447.4008
100	198.6887	-46.3607	-152.3280	311.2789	258.2953	238.4264
129	212.8631	-49.6151	-62.7652	111.8836	51.7708	93.2815
158	-104.5425	-83.1954	-83.9588	83.8154	215.5329	-108.2673
185	-50.6502	251.2783	-38.5558	295.3943	38.4281	-314.6611
213	-265.4907	476.8528	273.9860	-54.4105	-243.2343	-211.5379
247	-9.3279	126.0185	-53.1613	-164.8152	-27.4650	-80.5298
277	135.4277	-239.6647	224.0517	105.8974	77.9869	38.8658

Subject 6	**Position**			**Velocity**		
Walking Age (Days)	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF	COM_{ml}/TF	COM_{ap}/TF	COM_{rd}/TF
-28	-105.8242	-40.1086	191.2710	-107.5993	-138.1350	-288.0892
1	-27.0185	-147.0424	34.6335	206.4557	-124.1992	-225.7447
74	361.8458	93.1905	65.4863	-176.8774	-238.6399	-42.7474
96	-159.6478	-143.7079	-112.6159	173.9419	66.6171	-207.3485
124	399.1996	-40.5291	-28.3940	303.0680	-85.5067	-438.1429
188	117.7368	-11.9198	98.1283	72.7075	-169.1612	-104.6826
215	-8.1418	-121.2918	-416.3385	-204.6566	-235.3948	366.5892
270	-178.5114	47.2843	-250.6131	-364.4806	93.7790	-221.9220

Region-Related NTF Position Ellipse

Subject 1	Ellipse									
Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
-24	0.3863	0.3960	0.3790	0.3907	0.4038	0.3865	0.3624	0.3849	0.4349	0.4950
4	0.3153	0.3566	0.3138	0.3631	0.3317	0.3267	0.2930	0.2914	0.2988	0.3644
32	0.2423	0.2445	0.2624	0.2680	0.2850	0.2853	0.2678	0.3315	0.3316	0.3373
67	0.3290	0.4361	0.5559	0.5416	0.5090	0.5623	0.6336	0.5439	0.3491	0.2338
93	0.3014	0.2893	0.3292	0.3602	0.3627	0.3293	0.3340	0.3838	0.3686	0.4223
121	0.3088	0.2680	0.2790	0.3032	0.2876	0.3159	0.3016	0.3291	0.3378	0.3720

156	0.3417	0.3605	0.3710	0.3669	0.3742	0.3781	0.3756	0.3981	0.4351	0.5190
184	0.3783	0.3820	0.3864	0.3547	0.3577	0.4102	0.2989	0.3252	0.3932	0.4945
213	0.4477	0.4151	0.4057	0.3635	0.3348	0.3404	0.3448	0.3297	0.2896	0.4105
248	0.4192	0.5720	0.4299	0.4516	0.4068	0.2776	0.2421	0.4841	0.5439	0.5811
274	0.2872	0.3251	0.3542	0.3135	0.3137	0.3329	0.3784	0.3728	0.4474	0.5521

Subject 2	Ellipse									
Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
-12	0.2231	0.2720	0.2748	0.2879	0.2910	0.2776	0.2891	0.3142	0.3549	0.3767
9	0.3273	0.3013	0.2944	0.2944	0.3151	0.3314	0.3013	0.3736	0.4305	0.6274
37	0.3930	0.4225	0.4188	0.4471	0.4071	0.4614	0.5117	0.4895	0.4895	0.4886
58	0.4131	0.4281	0.4191	0.4353	0.4559	0.4903	0.5076	0.4321	0.4598	0.4460
93	0.4877	0.4810	0.4753	0.5025	0.5120	0.5291	0.4852	0.5533	0.5667	0.6435
156	0.2370	0.2379	0.2239	0.2428	0.2471	0.2500	0.2524	0.2967	0.3209	0.3918
185	0.3140	0.3016	0.3021	0.3176	0.3340	0.3764	0.3798	0.3606	0.3763	0.4691
213	0.4785	0.3992	0.3919	0.4336	0.3761	0.4153	0.3772	0.4142	0.4562	0.4428
247	0.4757	0.5384	0.5270	0.5186	0.5095	0.5104	0.5385	0.5342	0.5564	0.5206
268	0.3887	0.3516	0.3459	0.3338	0.3378	0.2984	0.3569	0.3469	0.3156	0.4560

Subject 3	Ellipse									
Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
33	0.3279	0.3699	0.3347	0.3691	0.3511	0.3276	0.3341	0.3167	0.3303	0.4743
72	0.3893	0.3061	0.2762	0.4219	0.4391	0.3865	0.3825	0.3666	0.3511	0.3657
114	0.3140	0.3576	0.3418	0.3494	0.3479	0.3368	0.3496	0.2902	0.3061	0.3722
149	0.5802	0.5467	0.4842	0.4931	0.4925	0.5001	0.4894	0.4765	0.4762	0.5088
184	0.4119	0.3881	0.3635	0.3754	0.3771	0.3809	0.3755	0.4054	0.4341	0.4628
211	0.3617	0.3985	0.3990	0.3683	0.4055	0.3978	0.4499	0.4832	0.5196	0.4527
249	0.4369	0.3902	0.3778	0.3642	0.3765	0.3799	0.3795	0.3523	0.3431	0.3153
270	0.4390	0.3935	0.3970	0.4005	0.4025	0.3990	0.3773	0.4673	0.4827	0.5172

Subject 4	Ellipse									
Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
2	0.5389	0.5960	0.6789	0.6541	0.5267	0.5334	0.4889	0.3494	0.3408	0.5516
36	0.4479	0.4496	0.4687	0.4427	0.4311	0.4412	0.4296	0.4331	0.4483	0.4035
69	0.3250	0.3574	0.3359	0.3518	0.3537	0.3478	0.3460	0.3443	0.3098	0.3719
100	0.5050	0.5113	0.4615	0.3039	0.5023	0.4620	0.4316	0.3805	0.4265	0.3417
133	0.5713	0.5050	0.4938	0.4478	0.4916	0.4552	0.4481	0.4538	0.4412	0.3786
156	0.2914	0.3126	0.3133	0.3246	0.3238	0.3398	0.3356	0.4175	0.4389	0.3951
189	0.4906	0.4768	0.3977	0.3986	0.4272	0.4212	0.4491	0.5887	0.5628	0.5592

Subject 5	Ellipse									
Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
-18	0.4853	0.4799	0.4692	0.4473	0.4297	0.4620	0.4720	0.4596	0.3906	0.3660
3	0.3616	0.4061	0.3949	0.3980	0.3946	0.3914	0.4161	0.3890	0.4108	0.5052
31	0.3762	0.3605	0.2952	0.2901	0.3192	0.3138	0.3141	0.3349	0.3755	0.4103
59	0.4740	0.4577	0.4737	0.4703	0.4670	0.4431	0.4295	0.4275	0.4042	0.3948
100	0.2653	0.2732	0.2988	0.3104	0.2975	0.2815	0.2990	0.3058	0.3174	0.4095
129	0.2883	0.2706	0.2726	0.2792	0.2984	0.3324	0.2945	0.3269	0.3116	0.4687
158	0.2568	0.2534	0.2546	0.2749	0.2928	0.3349	0.3220	0.3240	0.3465	0.3636
185	0.2784	0.2958	0.2788	0.3020	0.3167	0.3462	0.3694	0.4064	0.3366	0.3796
213	0.2137	0.2629	0.2850	0.2756	0.2746	0.2487	0.2709	0.3000	0.3236	0.4957
247	0.2745	0.2775	0.2855	0.2761	0.2843	0.3116	0.3061	0.3054	0.3556	0.4583
277	0.4064	0.3518	0.3572	0.3312	0.3473	0.3873	0.3652	0.3662	0.3950	0.4695

Subject 6	Ellipse									
Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
-28	0.3687	0.3702	0.3530	0.3485	0.3664	0.3491	0.3373	0.3379	0.3223	0.3287
1	0.3512	0.3567	0.3560	0.3495	0.3588	0.3825	0.3750	0.3960	0.4330	0.3736
74	0.3776	0.3823	0.4080	0.3872	0.4048	0.4178	0.4203	0.4264	0.4114	0.4091
96	0.3379	0.3519	0.3920	0.4101	0.3916	0.4162	0.3944	0.4248	0.3941	0.4217
124	0.2283	0.2401	0.2753	0.2682	0.2699	0.2969	0.2845	0.3383	0.2759	0.3870
188	0.4815	0.5273	0.5882	0.5692	0.5489	0.5351	0.5357	0.5726	0.5862	0.5725
215	0.3160	0.3095	0.3375	0.3584	0.3573	0.3550	0.3608	0.3498	0.4228	0.5298
270	0.3742	0.3793	0.3955	0.4471	0.4394	0.4221	0.4513	0.4379	0.5032	0.5808

Velocity Ellipse

Subject 1	Ellipse									
Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
-24	0.3863	0.3901	0.3911	0.4007	0.3759	0.3732	0.4109	0.4015	0.4312	0.4587
4	0.3292	0.3296	0.3606	0.3495	0.3625	0.3422	0.3367	0.3332	0.3426	0.2844
32	0.2613	0.2616	0.2740	0.2642	0.2908	0.3037	0.3054	0.2954	0.3218	0.3600
67	0.4926	0.4490	0.4748	0.5455	0.5598	0.5037	0.4315	0.3998	0.5535	0.4957
93	0.3383	0.3710	0.3707	0.3654	0.3424	0.3267	0.3650	0.3764	0.3698	0.3907
121	0.2679	0.2901	0.2956	0.2867	0.3143	0.3296	0.3237	0.3295	0.3420	0.3687
156	0.3838	0.3871	0.3948	0.3856	0.4088	0.3846	0.4004	0.4076	0.3965	0.4116
184	0.3589	0.3554	0.4319	0.4296	0.4251	0.3880	0.3761	0.4284	0.4170	0.3859
213	0.3734	0.3703	0.3547	0.3598	0.3350	0.3450	0.3226	0.3683	0.4112	0.3990
248	0.3227	0.3414	0.3907	0.4178	0.5203	0.3970	0.4829	0.5281	0.5592	0.5219
274	0.3028	0.3652	0.3728	0.3694	0.3968	0.3932	0.3805	0.3997	0.4238	0.4231

Subject 2 Ellipse

Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
-12	0.2868	0.2640	0.2873	0.2675	0.2863	0.3018	0.2977	0.3171	0.3229	0.4105
9	0.2958	0.3037	0.3132	0.3359	0.3269	0.3822	0.3804	0.4137	0.4166	0.3907
37	0.4894	0.4700	0.4538	0.4581	0.4579	0.4345	0.4524	0.4213	0.4375	0.4562
58	0.4462	0.4509	0.4536	0.4463	0.4301	0.4460	0.4442	0.4411	0.4697	0.4357
93	0.4853	0.5031	0.5245	0.5179	0.5009	0.5411	0.5727	0.5290	0.5547	0.5274
156	0.2203	0.2492	0.2317	0.2373	0.2418	0.2682	0.2713	0.3313	0.3022	0.3692
185	0.3181	0.3369	0.3433	0.3387	0.3647	0.3584	0.3673	0.3598	0.4081	0.4109
213	0.3930	0.3975	0.4048	0.4229	0.3878	0.4032	0.3919	0.4004	0.4177	0.4351
247	0.5356	0.5379	0.5284	0.5181	0.5190	0.5503	0.5286	0.5177	0.5142	0.4659
268	0.3391	0.3314	0.3365	0.3404	0.3356	0.3485	0.3355	0.3674	0.3854	0.4249

Subject 3 Ellipse

Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
33	0.3378	0.3466	0.3465	0.3722	0.3169	0.3142	0.3074	0.3297	0.3974	0.3562
72	0.3112	0.4071	0.4059	0.3802	0.3600	0.3365	0.3734	0.3941	0.3936	0.4141
114	0.2802	0.3072	0.3574	0.3570	0.3565	0.3826	0.3460	0.3116	0.3276	0.3275
149	0.5015	0.4855	0.4987	0.4954	0.4643	0.4601	0.5093	0.5246	0.5710	0.5651
184	0.3643	0.3864	0.3883	0.3777	0.3669	0.4034	0.4728	0.4480	0.4910	0.4437
211	0.3908	0.3990	0.4072	0.4149	0.4164	0.3964	0.3977	0.3776	0.3791	0.4649
249	0.3694	0.3805	0.3640	0.3754	0.3916	0.3952	0.3732	0.3599	0.3517	0.3084
270	0.4208	0.4234	0.4023	0.4190	0.4458	0.4580	0.4328	0.4391	0.4017	0.4425

Subject 4 Ellipse

Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
2	0.5021	0.5528	0.5214	0.5057	0.5156	0.4806	0.5101	0.4872	0.4663	0.5759
36	0.4403	0.4493	0.4279	0.4407	0.4346	0.4326	0.4459	0.4314	0.3942	0.4577
69	0.3356	0.3428	0.3598	0.3432	0.3426	0.3310	0.3362	0.3339	0.3386	0.3759
100	0.4023	0.4225	0.4244	0.4566	0.4237	0.4381	0.4836	0.4514	0.5225	0.4713
133	0.4968	0.4864	0.4774	0.4638	0.4887	0.4667	0.4314	0.4554	0.4550	0.4341
156	0.3013	0.3214	0.3136	0.3500	0.3204	0.3050	0.3385	0.3805	0.4097	0.4534
189	0.4629	0.4739	0.4677	0.4878	0.5101	0.5059	0.4657	0.4578	0.4737	0.5291

Subject 5 Ellipse

Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
-18	0.4546	0.4684	0.4636	0.4443	0.4499	0.4636	0.4405	0.4138	0.4213	0.4255
3	0.3887	0.3990	0.3484	0.3632	0.3877	0.3912	0.4191	0.4549	0.4293	0.4829

31	0.2880	0.3151	0.3330	0.3354	0.3530	0.3365	0.3487	0.3402	0.3270	0.4006
59	0.4565	0.4641	0.4680	0.4517	0.4437	0.4577	0.4668	0.4263	0.4319	0.3955
100	0.2873	0.2889	0.2799	0.2869	0.2990	0.2956	0.3108	0.3207	0.3534	0.3759
129	0.2895	0.2936	0.3026	0.2812	0.3069	0.3195	0.3226	0.3165	0.3179	0.3343
158	0.2723	0.2935	0.2986	0.3074	0.3009	0.3211	0.3212	0.3356	0.3262	0.3411
185	0.3127	0.3279	0.3189	0.3264	0.3179	0.3196	0.3050	0.3374	0.3368	0.3422
213	0.2644	0.2883	0.3028	0.3079	0.2840	0.2942	0.3394	0.3122	0.2972	0.3254
247	0.2650	0.2794	0.2749	0.2973	0.3285	0.3438	0.3697	0.3595	0.3529	0.4056
277	0.3349	0.3415	0.3533	0.3822	0.3813	0.3976	0.3858	0.4045	0.4230	0.4226

Subject 6	Ellipse									
Walking Age (Days)	1	2	3	4	5	6	7	8	9	10
-28	0.3461	0.3520	0.3418	0.3526	0.3551	0.3449	0.3347	0.3446	0.3834	0.3615
1	0.3598	0.3654	0.3691	0.3577	0.3690	0.3530	0.3665	0.3576	0.3777	0.4203
74	0.4171	0.4318	0.4242	0.4233	0.4277	0.4208	0.4175	0.3775	0.3779	0.3480
96	0.3718	0.3807	0.3899	0.3919	0.3753	0.3708	0.3947	0.4409	0.4727	0.4146
124	0.2874	0.2823	0.2848	0.2691	0.2961	0.2864	0.2789	0.3054	0.3252	0.3321
188	0.5547	0.5490	0.5406	0.5420	0.5568	0.5618	0.5634	0.5569	0.5455	0.5257
215	0.3561	0.3612	0.3524	0.3630	0.3585	0.3702	0.3704	0.3726	0.3891	0.4153
270	0.4258	0.4335	0.4527	0.4447	0.4205	0.4112	0.4238	0.4584	0.4800	0.4913