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The Control of Posture in Newly Standing Infants is Task-Dependent

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Abstract

The postural sway patterns of newly standing infants were compared under two conditions: standing while either holding or not holding a toy. Infants exhibited a lower magnitude of postural sway and more complex sway patterns when holding the toy. These changes suggest infants adapt postural sway in a manner that facilitates visually fixating on and stabilizing the toy in their hand. When simply standing, infants exhibited postural sway patterns that appeared to be more exploratory in nature. Exploratory sway patterns may allow infants to learn the affordances of their new standing posture. These results demonstrate newly standing infants are capable of task-dependent postural control.

The Control of Posture in Newly Standing Infants is Task Dependent

Numerous factors, including a high center of mass (Sinclair, 1989), sensori-motor impairments (e.g., Gori, Del Viva, Sandini, & Burr, 2008), and an underdeveloped neuromuscular system (McGraw, 1943), contribute to the limited mobility and protracted postural development of human infants. Indeed, postural milestones such as raising the head and independently sitting take months to develop. Independent stance, a difficult posture requiring infants to maintain their center of mass within a relatively small base of support does not emerge until almost one year-of-age. The postural deficits of infants have been linked to the slow emergence of other non-postural goal-directed behaviors (Thelen & Spenser, 1998; Gahery & Massion, 1981). For example, although infants possess sufficient strength to move their arm after birth, the development of goal-directed reaching is delayed in part due to an immature postural system (Rochat, 1992). When given external postural support, the spontaneous and inaccurate arm movements of pre-reaching infants become more organized, resulting in mature reaching movements (von Hofsten, 1982). Even after the onset of reaching, 6-month-olds exhibit more mature reaches with external postural support (Hopkins & Rönnqvist, 2001). These studies demonstrate the postural system must support and control the body against gravity before the infant can adequately perform goal-directed reaching tasks.

Past research has mainly examined the role of posture in the development of motor milestones by experimentally manipulating postural stability. These studies typically viewed posture as a foundation for other motor behaviors, thus emphasizing the necessity of postural stabilization. However, stabilizing posture does not always facilitate task performance. Maintaining a rigid posture can reduce the flexibility and adaptability of the postural system and its ability to attenuate body perturbations (Hamill, Haddad, Heiderscheit, & Van Emmerik, 2006). When performing most routine (less demanding) activities, postural movements in adults are not tightly constrained (Riccio & Stoffregen, 1988; Haddad, Ryu, Seaman, & Ponto, 2010). However, when performing precision demanding tasks, postural sway is minimized since extraneous body movements could reduce accuracy and impede the performance of the precision task (Balasubramaniam, Riley, & Turvey, 2000). Thus, in adults, the control of posture is task-dependent. Learning task-dependent postural control is likely a critical component of motor development.

Assessing posture and balance in infants

Posture is typically assessed by collecting linear force and moment data from a force plate. Center of pressure (CoP), the instantaneous location of the vertical ground reaction force vector, is then calculated to provide a representation of postural sway in the anterior-posterior and medial-lateral directions. When infants first learn to stand, they exhibit an increased CoP magnitude, velocity, frequency, and variance as compared to adults (Chen, Metcalfe, Chang, Jeka, & Clark, 2008; Riach & Starkes, 1994; Riach & Hayes, 1987). The measures often used to quantify CoP are time-independent since their calculation is not influenced by the temporal evolution of the CoP time-series. One limitation of time-independent measures is that information regarding the structure of the signal is lost. For example, two CoP signals, one that is regular (somewhat sinusoidal) and one that is complex (containing seemingly random fluctuations) could have a similar magnitude and variance despite having different structures.

Examining the structure of the CoP signal has been shown to provide insight into the control of posture that is not captured using traditional time-independent measures (Haddad, Van Emmerik, Wheat, & Hamill, 2008; Stergiou, Harbourne, & Cavanaugh, 2006). Many analytical techniques, inspired from dynamical systems theory, have been developed to quantify these time-dependent fluctuations. One measure used in postural research is sample entropy ($\text{Samp}_{\mathbf{EN}}$) (Rhea, Silver, Hong, Ryu, Studenka, Hughes, & Haddad, 2011). $\text{Samp}_{\mathbf{EN}}$ provides information regarding the degree of complexity and regularity inherent in the signal. A regular (more sinusoidal) CoP signal exhibits a lower value of $\text{Samp}_{\mathbf{EN}}$ whereas a more complex CoP signal exhibits a higher value of $\text{Samp}_{\mathbf{EN}}$. The benefit of using $\text{Samp}_{\mathbf{EN}}$ to quantify CoP is best understood by examining the nature of the CoP signal. In healthy individuals, numerous sensori-motor feedforward and feedback processes act over multiple time-scales to maintain balance against internally and externally generated perturbations (Collins & De Luca, 1994). The CoP signal is ultimately a net representation of the corrective postural movements generated about the body's degrees of freedom (ankle, hip, knee, and in some cases the upper body) by these complex processes (Newell, 1997). Thus, a more complex and irregular CoP structure is observed when corrective postural movements are generated about multiple degrees of freedom. Consequently, if postural sway results from movement over fewer degrees of freedom (e.g. a rigid posture is adopted), less complex CoP patterns emerge (Newell, 1997). Less complex postural patterns can be indicative of a less healthy, less flexible, and less adaptable postural system. For example, sitting infants at risk of Cerebral Palsy exhibit less complex sway patterns compared to typically developing infants (Stergiou et al., 2006). CoP complexity also changes based on the constraints of a concurrently performed task (Donker, Roerdink, Greven, & Beek, 2007; Haddad et al., 2008), demonstrating optimal complexity is task-dependent.

The coordination of posture with other goal-directed behaviors in infants

Although postural sway changes as a function of development, it is unknown if newly standing infants properly control and modulate postural sway when performing a standing task. In the current study, we examine changes in the magnitude and complexity of postural sway that occur as infants perform two different standing conditions (standing while holding a toy and standing without holding a toy). The toys were typical commercially available hand-held toys. Minimizing postural sway would improve the infant's ability to properly attend to the toy. It was hypothesized infant's postural sway would change in a manner that affords interaction (visually fixating on and stabilizing the toy in their hand) with the toy, suggesting infants begin to control posture in a task-dependent manner soon after the emergence of independent stance. This hypothesis was based off research that found infants possess rudimentary adaptive postural control. Specifically, before 9-10 months of age, seated infants exhibit stereotyped postural responses when perturbed (Assaiante, 1998). With experience more adaptive responses emerge (Hadders-Algra, 2005). We posited that since sitting infants exhibit adaptive postural responses, this ability would also be present when standing. Essentially, standing task-dependent postural control may be an extension of adaptive strategies learned while sitting. Additionally, standing infants adapt postural sway to varying somato-sensory information (Metcalfe & Clark, 2000; Chen et al., 2008), suggesting environmental context and sensory information influences infant's postural control. Consequently, if the posture of newly standing infants is not adaptive, sway patterns would likely be stereotyped and independent of experimental manipulations.

Methods

Participants

Potential participants were identified from birth announcements in the local newspaper. Parents were sent a letter explaining the study and then contacted via phone. Interested parents were asked about the current motor abilities of their child. Children who were invited to participate could stand independently, but were not yet walking. Data were collected between when the child could stand for a minimum of 5-seconds but was not yet able to walk without assistance (could take no more than two steps before falling). On average, parents reported infants had been standing independently for approximately two-weeks at the time of data collection. Sixteen infants (9 females and 7 males; *M* age = 11mo, 3wks; *range* = 9;2 to 13;1) participated. Procedures were approved by the University Institutional Review Board.

Procedure

In each trial, the infant stood on a force plate (AMTI; Watertown, MA) while either holding a toy (toy-hold condition) or not holding a toy (no-toy condition). In the no-toy condition, the infant was not given anything to hold. In the toy-hold condition, the experimenter handed the infant a toy once they were standing on the force plate. In both conditions, the experimenter either lowered the infant onto the force plate in a standing position or allowed the infant to pull themselves into a standing posture using a chair adjacent to the force plate. Four trials were performed in each condition. A different age-appropriate toy - rattle (60g), duck (60g), toy phone (90g), and toy keys (70g) - was used in each toy-hold trial so the infant would not become bored with a particular toy. The weights of the toys were assessed using a pediatric strain gauge scale. The graspable area of all toys ranged from 1.2-1.4 cm in circumference. The typical inside hand circumference (50th percentile) for one-year-olds is 2.1 cm (National Institute of Standards and Technology, 1975). Thus, the toys were easily graspable. Trials from each condition were performed in alternating order. CoP was calculated using the force and moment data collected from the force plate at 120 Hz. A synchronized digital video recording was also captured.

Data Analysis

Assessing infant standing can be difficult since extraneous head or arm motion could potentially confound results by altering postural sway patterns between conditions. For example, in the no-toy condition, arm movements could occur since nothing is held. To ensure these confounds did not occur, a coding scheme similar to Chen et al. (2008) was used. Trained coders were used to identify the period of time during the trial when the infant was independently standing, attending to the toy (in the toy-hold condition), and was not making extraneous arm, body, or head movements. For reliability coding, a second coder examined 50% of the trials. There was 91% agreement between coders. A third coder was used to resolve any disagreement. It was determined that infants were independently standing when they were supporting 100% of their body weight (the vertical ground reaction force vector (Fz) from the force plate matched body weight). Arm and body movements were also detected by examining Fz. When the infant stands without making arm and body movements, Fz is stable and matches body weight. However, if the infant bounces or moves his/her arms (e.g. shakes the toy), center of mass will vertically oscillate resulting in Fz no longer matching body weight (it will also oscillate). The synchronized digital video recording was used to determine if the infant was attending to the toy (in the toy-hold trials) and not making extraneous head movements. In all trials, infants stood approximately 5-10-seconds before returning to a sitting posture. Out of the total standing time, a middle two-second portion of the CoP time series was analyzed.

Elliptical area (CoP$_{\mathbf{ellipse}}$) and sample entropy (Samp$_{\mathbf{EN}}$) of the net CoP trajectory were calculated from the CoP time-series. CoP$_{\mathbf{ellipse}}$ was calculated using the technique in Oliveira, Simpson, and Nadal (1996). This technique uses principle component analysis to determine the area of a best fit ellipse that encompassed the CoP data (Figure 1). Samp$_{\mathbf{EN}}$ of the net CoP trajectory was calculated using the algorithms developed by Richman and Moorman (2000). The CoP time-series was normalized to unit variance before calculating $\mathrm{Samp}_{\mathbf{EN}}$. The net CoP trajectory was calculated by summing the Euclidian distance between consecutive data points from the anterior-posterior and medial-lateral CoP time-series. The embedding dimension and radius parameter used to calculate $\mathrm{Samp}_{\mathbf{EN}}$ were set to 2 and 0.2 respectively. These input parameters have previously been found to be appropriate for unfiltered CoP data (Ramani, Seigle, Lagarde, Bouchara, & Bernard, 2009). $\mathrm{Samp}_{\mathbf{EN}}$ was calculated using unfiltered CoP data since filtering can impose non-physiological deterministic features onto the signal. Prior to calculating $\mathrm{CoP}_{\mathbf{ellipse}}$, data were filtered at 10 Hz using a fourth order low pass Butterworth filter. Although various algorithms are used to calculate CoP entropy (Rhea et al., 2011), we used $\mathrm{Samp}_{\mathbf{EN}}$. Given appropriate input parameters, $\mathrm{Samp}_{\mathbf{EN}}$ provides reliable measures of entropy using time-series as short as 100 data points (Richman & Moorman, 2000). Thus, $\mathrm{Samp}_{\mathbf{EN}}$ is well suited to calculate CoP entropy in infants who can only stand for a short duration of time. Differences between the two conditions were assessed using paired samples *t*-tests.

Results

$\mathrm{CoP}_{\mathbf{ellipse}}$ was smaller in the toy-hold condition ($M = 1200$ mm^2; $SE = 172$ mm^2) compared to the no-toy condition ($M = 1655$ mm^2; $SE = 140$ mm^2); $t(15) = 2.310$, $p<0.03$, $d=0.82$ (Figure 2a), indicating that infants reduced postural sway when holding a toy. Additionally, $\mathrm{Samp}_{\mathbf{EN}}$ was lower in the no-toy condition ($M =0.240$, $SE = 0.017$) compared to the toy-hold condition ($M = 0.289$, $SE = 0.023$); $t(15) = 2.312$, $p<0.05$, $d=0.94$ (Figure 2b), indicating that the CoP time-series was more complex (less regular) when infants held the toy.

Discussion

Task-dependent postural strategies in newly standing infants

Results support the hypothesis that newly standing infants alter postural sway to support a concurrently performed goal-directed task. Reducing CoP sway area likely improved the infant's ability to visually fixate on and stabilize the toy in their hand. Infants also adopted a more complex (less regular) CoP pattern when holding a toy. The increased entropy was somewhat counterintuitive given it is logical to expect infants would stiffen their body (exhibit lower values of CoP entropy) as a strategy to reduce CoP movements. Although an easy way to simplify movement control, a stiffening strategy may be less optimal when performing standing tasks. Utilizing and controlling more of the body's degrees of freedom results in an increased ability to attenuate perturbations, ultimately improving the flexibility and adaptability of the postural system and the infant's ability to efficiently perform a standing goal-directed task (Hamill et al., 2006). The current findings suggest infants may use an endpoint strategy when interacting with the toy, where low amplitude controlled movements are allowed at the individual degrees of freedom so that stability of the endpoint is maintained. These controlled movements likely allow the infant to better attenuate perturbations to balance that are generated while interacting with the toy. Similar endpoint strategies have been observed in adult posture and manual control. For example, the gun barrel of skilled marksmen is extremely stable despite variable but balanced movements at the arm joints. Consequently, novices stiffen their arm, a strategy that reduces movement at the individual joints but ultimately leads to random and uncontrolled fluctuations of the barrel (Arutyunyan, Gurfinkel, & Mirskii, 1968). Thus, controlled movements about the degrees of freedom involved in a goal-directed behavior, help maintain system stability, flexibility, and adaptability. Our results therefore suggest infants increase CoP complexity as a strategy to maintain smaller postural movements that afford efficient interaction with the toy.

In the no-toy condition, infants exhibited increased $\text{CoP}_{\textbf{ellipse}}$ and more regular CoP movements (lower $\text{Samp}_{\textbf{EN}}$). These sway characteristics, while not conducive to performing a concurrent goal-directed task, may serve an exploratory function. From the ecological approach to perception and action (Gibson, 1979; Gibson & Pick, 2000), exploratory movements are not goal-directed. Rather, the purpose of exploratory movements is to generate perceptual information regarding the interaction between the animal and environment. Exploratory movements provide a mechanism over which affordances are learned (Gibson & Pick, 2000; Adolph, 2002); possibilities for action are determined; and optimal solutions are generated (Thelen, Corbetta, Kamm, Spencer, Schneider, & Zernicke, 1993). Exploratory postural movements may be particularly important in infants given their rapid neuromuscular and anthropometric development that change affordances for action (Adolph, 2002). Since a stable CoP endpoint need not be maintained, exploratory patterns are more easily generated by minimizing the number of degrees of freedom recruited by the body. Essentially, it would be difficult for infants to maintain balance when generating large magnitude movements about multiple degrees of freedom.

Taken together, our results suggest that newly standing infants shift postural strategies in a manner that helps them accomplish immediate goals. When simply standing, exploratory postural strategies potentially allow the infant to learn the specific affordances of bipedal stance. However, when performing a goal-directed task, infants suspend exploratory postural movements and adopt an endpoint strategy that facilitates performance of the concurrent activity.

Development of the integration between posture and other goal-directed behaviors

Past research has demonstrated that inter-sensory integration, needed for optimal postural control, develops through childhood (Bair, Kiemel, Jeka, & Clark, 2007; Gori et al., 2008). Additionally, even by 10-years of age, the coordination between posture and manual control is not completely developed when performing a precision hand movement (Haddad, Claxton, Keen, Berthier, Riccio, Hamill, & Van Emmerik, 2012). Given the protracted development of optimal postural control, it is interesting that infants in the current study demonstrated adaptive task-specific postural strategies. Three potential possibilities can explain this finding. First, it is possible these postural strategies were learned while independently sitting. Many standing balance constraints also exist while in a sitting posture. In both instances, the body must be supported against gravity. When first learning to sit, remaining upright is difficult and infants often topple over. However, with experience, infants can maintain a sitting posture while performing potentially destabilizing activities, such as leaning to grasp an object (Rochat, Goubert, & Senders, 1999). Second, the observed adaptive postural strategies may have developed during the limited time infants were independently standing. Third, task-specific postural control may be inherent to stance and not a learned behavior. A longitudinal study that follows infants from a sitting to standing to walking posture is needed to fully explore these possibilities. In conclusion, newly standing infants, with limited standing experience, exhibit either exploratory or performatory postural strategies depending on the constraints of a concurrent goal-directed task.

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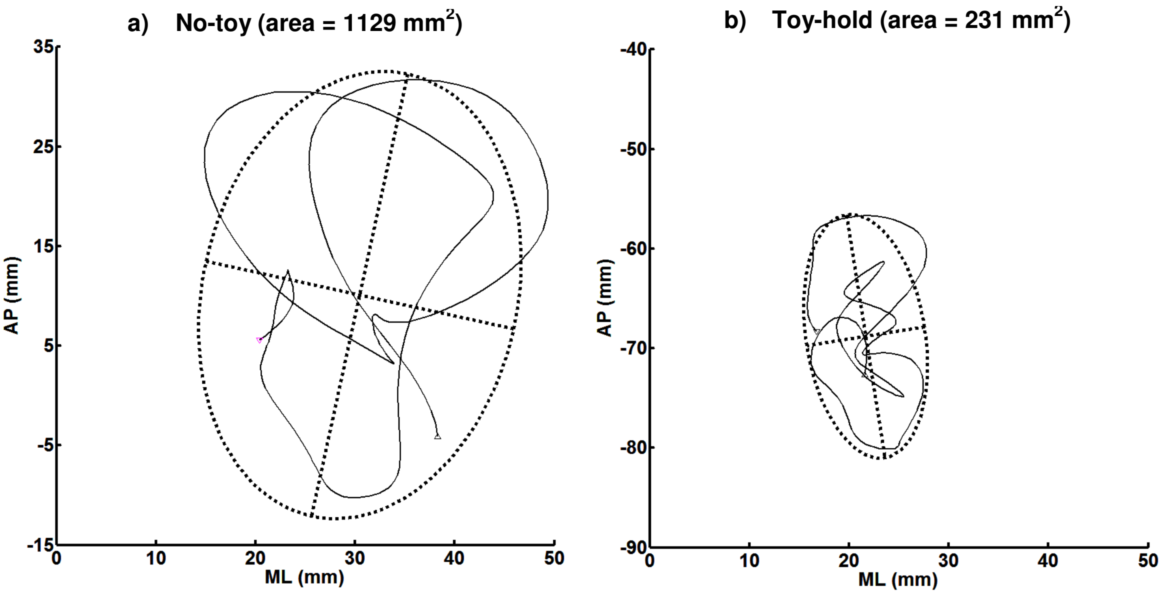

Figure 1: Example illustrating an ellipse fit to the CoP during a) no-toy and b) toy-hold condition. The solid black trajectory is the center of pressure over two-seconds of independent stance. The ellipse (dotted black line) was then fit to the 95% of the center of pressure data points. A 95% fit criteria is commonly used to remove the influence of outlying data points. The area of the ellipse was then quantified.

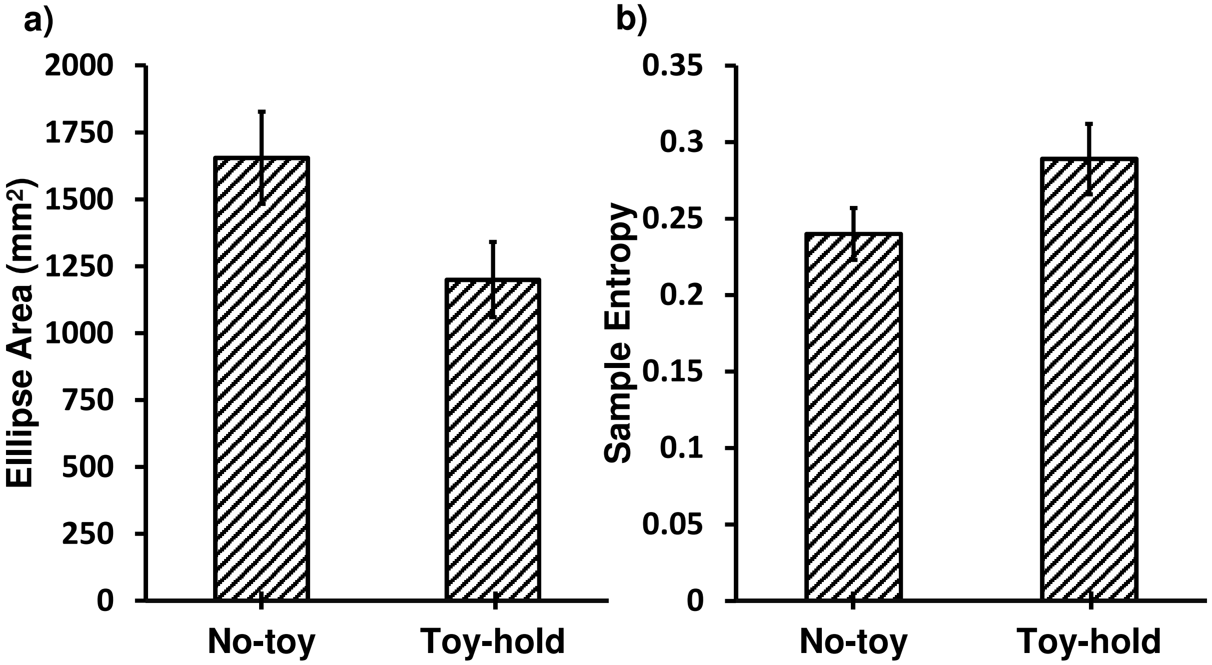

Figure 2: average a) elliptical area and b) sample entropy +/- SE in the no-toy and toy-hold conditions.