Sit happens: Does sitting development perturb reaching development, or vice versa?

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ABSTRACT

The development of reaching and of sitting during the first year of life is typically studied as separate yet related behaviors. Interestingly, very soon after learning to reach, 4–7-month-old infants start coordinating their arms with their trunk and legs for sitting. In this longitudinal study, we focused, for the first time, on how infants learn to use their arms for the dual tasks of reaching for objects while providing arm support as they learn to sit. We hypothesized that the use of arms for support during sitting development would be a temporary perturbation to reaching and result in a nonlinear progression of reaching skill.

Eleven infants were studied monthly from the time they began to prop sit to the time of sitting independence (5–8 months of age). Behavioral coding, kinematics, and electromyography (EMG) characterized reaching and posture while infants sat as independently as possible. Results revealed significant changes across time in trunk movement and hand use as infants transitioned through three stages of sitting: with arm support, sitting briefly without arm support, and sitting independently. Infants used their hands more for contacting objects and less for posture support linearly across time. In contrast, changes in posture control as indicated by pelvis and trunk movement demonstrated a U-shaped curve with more movement of these two body segments during the middle stage of sitting than in the first or last stage. During the middle stage of sitting infants reached persistently even though posture control, measured by pelvis and trunk movement, appeared to be significantly challenged. Muscle activation consisted of tonic and variable combinations of muscle pairings in early sitting. As infants progressed to sitting without hand support, variable but successful strategies utilizing lower extremity muscles in a tight linkage with reach onset emerged to provide prospective control for reaching. Our findings support the contention that reaching both drives the development of sitting in infancy as well as perturbs sitting posture, factoring into the assembly of the complex dual sit–reach behavior that supports and expands flexible interaction with the environment.

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1. Introduction

This study seeks to better understand how the experiences encountered by infants during the initial development of sitting impact the continued development of reaching. Reaching, which emerges around 4–5 months of age (Thelen, Corbetta,

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Kamm, & Spencer, 1993; von Hofsten, 1991), provides the first independent exploration of objects in the local environment. Not surprisingly, reaching creates an impact on perceptual, cognitive and social development (Corbetta, Thelen & Johnson, 2000) including knowledge about objects (Needham, 2000; Ruff, Saltarelli, Capozzoli, & Dubiner, 1992) and plans for action with objects (Claxton, Keen & McCarty, 2003). Sitting also begins emerging around 4–5 months of age as infants gain head and upper trunk control in supported sitting. Corresponding changes in perceptual, cognitive and social development appear to be related to the achievement of sitting (Out, Soest, van Savelsbergh, & Hopkins, 1998; Rochat, 1992; Soska, Adolph, & Johnson, 2010). Unlike reaching, which is a behavior that allows infants to be successful interacting with objects shortly after the behavior first emerges, sitting takes an additional 3–4 months to transition from infants using their arms for support (aka 'prop sitting') to independent sitting (Folio & Fewell, 2000; McGraw, 1945; Piper, Pinnell, Darrah, Maguire, & Byrne, 1992). Thus, sitting and reaching overlap both in developmental time, and in relation to other areas of development.

We propose that learning to combine sitting and reaching requires a period of problem solving to plan and execute movement and exploration of objects. Specifically, newly sitting infants who are offered objects are faced with a dilemma that must be solved in real time: risk falling by using one or both arms to reach for the object, or remain safely prop sitting but inhibit the drive to explore a reachable object. The general purpose of this study was to test hypotheses regarding the process by which infants learn to combine these two behaviors.

1.1. Reaching and sitting development

In spite of the obvious interaction of these two behaviors, studies of reaching and sitting development typically focus on each behavior separately. For reaching, infants are generally studied when they are in a supported supine or reclined sitting position with reduced postural control requirements. For example, Thelen et al. (1993) stabilized infants' trunk in a specialized reclined seat during reaching throughout the first year of development for quantification of the reach. Savelsbergh and van der Kamp (1994) also utilized a specialized seat to reduce the influence of limits in postural control when examining infant reaching in different orientations to gravity. Together, these studies found individual differences between children in the way reach developed, as well as differences within each child depending on their position in space (vertical sitting or reclined sitting). Infant reaching generally becomes smoother and more accurate from the emergence of reaching at 4 months to skillful reaching at 8 months of age (von Hofsten, 2004; Thelen et al., 1993). However, the constrained posture of the infants in these studies limits the translation of these findings to everyday, naturally occurring behavior, which involves the ongoing coordination of reaching and sitting.

The question remains whether reaching enhances or challenges the gradual emergence of sitting. For example, independently sitting infants reached longer distances and more frequently compared to infants not yet sitting independently (Rochat & Goubet, 2000). Independent sitting is also linked to the attainment of object manipulation skill (Adolph & Berger, 2011), and is thought to provide variable opportunities for the child to visually orient to and regard the object being manipulated (Soska et al., 2010). Moreover, once sitting and reaching begin to co-occur, this linkage affects the development of language and cognition (Iverson, 2010; Smith & Sheya, 2010) as well as the emergence of crawling and walking (Corbetta & Bojczyk, 2002; Goldfield, 1989). Thus, the motor skill of sitting has been implicated as one of the factors important to the progression of overall skill in the motor domain, and thus has been quantified using both behavioral and kinematic techniques.

Quantification of motor coordination during sitting development indicates changes in patterns of muscle activation, kinematics and/or key behaviors related to increasing stability. Muscle activity patterns became more tightly timed to the intended action of the child (reaching or controlling the trunk in sitting), and more specific and accurate muscle responses emerge as sitting became more stable (Harbourne, Giuliani, & Mac Neela, 1993; Hadders-Algra, Brogren, & Forssberg, 1996a; Woollacott et al., 1987). In addition, the variability of muscle activation to control a postural perturbation in sitting decreases as sitting improves (Harbourne et al., 1993). Trunk and pelvic kinematics change as sitting improves. For example, trunk velocity in the forward direction decreases over developmental time with the removal of support in prop sitting infants, indicating that infants gain increasing control of their trunk and head mass over time (Harbourne et al., 1993). Infants change from an in-phase to an out of phase relationship of thorax–pelvis motion as they progress from prop sitting to sitting without arm support, indicating greater axial control of posture (Kyvelidou et al., 2009). Observational techniques describe similar increases in straightness and verticality of the trunk as sitting develops (McGraw, 1945; Piper et al., 1992). These details of sitting progression have not previously been studied in relation to reaching, so the interaction and coordination of these two skills is unclear. Thus, although much has been learned from studying sitting and reaching behaviors separately, the present study built on the limited literature describing how infants solve the problem of staying vertical while using the arms for reaching, which we briefly summarize next.

1.2. Does the initial development of sitting advance or constrain reaching?

The development of sitting may advance the continued progression of reaching. Spencer, Vereijken, Diedrich, and Thelen (2000) posited that sitting independently was associated with stable reaching. For example, Kamm (1995) coded the reaching and sitting progression in 5 infants from 8 weeks of age until they had one month of sitting experience. Vertical orientation had a facilitative effect on the frequency and skill of reaching. She proposed that postural control and reaching develop as a unit as the infant learns control of the head and body for vertical orientation. Experience reaching for objects was correlated

to improved postural stability in infants sitting on a moving platform, with more experienced reachers showing more mature postural reactions as measured by electromyography (EMG) (Hadders-Algra, Brogren, & Forssberg, 1996b). Thus, sitting and reaching are complimentary once infants have experience in both. But what about the key period in which reaching has been established in supported positions, and the infant now wants to reach from the new, unstable position of self-supported sitting?

The initial development of sitting may constrain the continued progression of reaching. Rochat and Goubet (1995) examined infant reaching and sitting behaviors in a cross-sectional comparison of sitters, non-sitters, and adult supported non-sitters. Infants who were not independent sitters did not utilize the trunk to extend their reach. Interestingly, whenever non-sitters were provided pelvic support they showed a precocious ability in real time to extend their reach using their trunk. Thus, infants' postural instability may constrain the adaptability of their reaching to more distant objects. Moreover, these researchers proposed that during the development of reaching, infants who are new to self-supported sitting understand their level of stability and the perceived "reachability" of a nearby object. Consequently, they only attempt a reach when they can avoid a loss of verticality through use of their balance and trunk control (Rochat, Goubet & Senders, 1999). This implies that infants may prioritize postural stability to avoid a fall, and thus alter or inhibit reaching if posture is challenged.

Taken together, these studies outline a general relationship between sitting independence and reaching: sitting emergence may initially inhibit reaching as the infant must use the arms preferentially for postural support, but then enhance reaching when sitting is independent. Several basic questions remain to be addressed. This longitudinal study addresses the issue of how sitting and reaching interact developmentally, and whether the development of independent sitting perturbs or interrupts the ongoing advancement of reaching. We predicted that infants' reaching would be perturbed by their early attempts at self-supported sitting for 3 reasons: (1) reaching is an established skill compared to the new skill of sitting; (2) poor sitting results in falling, thus use of the arms to maintain support would take precedence over reaching; and (3) sitting itself demands significant planning and infants would not be able to quickly plan for two relatively new skills at the same time. Thus, we hypothesized:

(1) An interruption of the progression of hand use to either (a) contact objects, or (b) provide postural support as sitting progresses to independence.
(2) Progressively decreased movement of the trunk and pelvis as sitting posture control emerges.
(3) Increased coupling of synergistic muscles of the arm, legs and trunk as sitting becomes independent.

2. Methods

2.1. Subjects

Eleven infants were recruited between the age of 4 and 5 months and participated after their guardians provided informed consent as approved by the University of Nebraska Medical Center Institutional Review Board. All infants were between the 25th and 75th percentile for height and weight with a normal birth history. Infants entered the study when they were at stage 1 sitting, also known as 'prop sitting' (Harbourne & Stergiou, 2003; Harbourne, Willett, Kyvelidou, Deffeyes, & Stergiou, 2010). Entry criteria included: Head control such that when supported at the mid-trunk; head control maintained for over one minute without bobbing; sitting for 30 s while propping with hands on floor or legs to lean on arms for support while maintaining head control; infant unable to maintain balance in the prop sit position without at least one hand for support; and, reaching when supported in an infant seat or in supine. These criteria were determined by parent report over the phone and confirmed by testing on the day of the experiment. All infants reached consistently when supported either in a seat or in supine at entry to the study, which was verified immediately prior to testing in the lab. Infants were also tested on the gross motor section of the Peabody Developmental Motor Scale-2 to assure age appropriate skills (Folio & Fewell, 2000). Criteria for the stages of sitting (Harbourne & Stergiou, 2003) were:

Stage 1 sitting: The infant sits for at least 30 s propping on both arms without falling; the infant may momentarily sit without arm support, but quickly (within 5 s) returns to a position of both arms propping to remain upright.
Stage 2 sitting: The infant sits for at least 30 s without falling and without use of the hands for full postural support; the infant reaching for toys in sitting often disrupts balance.
Stage 3 sitting: The infant sits for 5 min or more without falling; the infant reaches for toys in independent sitting with both hands without disrupting balance.

2.2. Design

We used a repeated-measures, longitudinal design, beginning at the time of prop sitting (stage 1 sitting) and ending when the infant sat independently without arm support (stage 3 sitting). Each infant made 3 visits to the lab with each visit corresponding to stage 1 (mean age = 4.5 months (range = 3.5–6 months), stage 2 (mean age = 5.7 months (range = 5–6.5 months), or stage 3 sitting skills (mean age = 7 months (range = 6–7.75 months), which resulted in visits of approximately

Fig. 1. Infant prepared for data collection. Markers for body segment measurement with the VICON system appear as lighted spheres.

once per month. The timing of each lab visit was determined by phone calls to the parent to monitor sitting skill and confirmed at the lab visit.

2.3. Instrumentation, materials, and measurement

Data collection occurred at the Munroe Meyer Institute at the University of Nebraska Medical Center using a Vicon 370 3D Motion Capture System (Vicon Motion Systems). The VICON 370 system included a 64-channel, 12-bit A/D converter and a computer (1 GHz PC; VICON Motion Systems). Data acquisition and processing were controlled through VICON 370 v. 2.5 software (Oxford Metrics Ltd., Oxford, UK). Video of each trial was also collected using two Panasonic video cameras (Model 5100 HS) and a Panasonic Digital AV Mixer (Model WJ-MX30). The cameras were positioned to record a side and a rear view of the infant. Motion analysis was performed with a 6 camera VICON analysis system for three-dimensional kinematic data. However, in this paper we only report data from the sagittal plane. The decision to use only sagittal plane data was made after an initial first pass through the kinematic data revealed missing segments of data from several VICON cameras in approximately 30% of the trials. We then decided to use only the sagittal plane data because the cameras necessary to calculate sagittal plane kinematics supplied continuous data streams without missing data. The other cameras, necessary for a complete 3D analysis, often lost track of the infant's markers because of unexpected movement of the either the infant or the adults who had to closely guard the sometimes unstable and unpredictable infant. In addition, hypotheses one and two require primarily the sagittal view for analysis because the primary movement displacement takes place in the sagittal plane. Plastic spherical reflective markers, 1/2 in. in diameter, were affixed to the infant's skin at the joint centers of the shoulder, elbow, wrist, hip, C7, lumbar spine at the PSIS, dorsum of the foot and head (Fig. 1). Although we attempted to measure head position by a marker attached to a headband, not all infants tolerated the headband. More problematic, the headband could not be placed reliably across sessions, and the round shape of the head allowed displacement of the headband within the session (see Fig. 3b). In the end, we eliminated head kinematics because the infants had full head control by visual observation from the onset of the study, and we felt the measure was not capturing head position changes over time. Kinematic data was sampled at 60 Hz, and was synchronized within the VICON system with the EMG.

Electromyography, using bipolar surface electrodes with onsite preamplification (GCS67 Therapeutics Unlimited), recorded muscle activity for 5 muscles: biceps and triceps of the right arm, lumbar paraspinals on the right side of the trunk, and hamstrings and quadriceps of the right leg. Myopotentials passed through an offsite amplifier (2000×), then were sampled digitally at 960 Hz and stored electronically for later analysis.

The electrodes were attached with double-sided tape, with a small amount of electrode gel between the electrode and skin to improve signal conduction. The electrodes on the arm and leg were secured with a light elastic wrap to keep them in place and prevent the infant from pulling them off. EMG data was only available for 8 infants, due to infant tolerance or equipment malfunctioning. If the infant showed signs of stress such as yawning, vocalizations of stress, or pulling away, only the kinematic markers were placed and the EMG electrodes were not used, in order to shorten the preparation time and allow the infant to accomplish some data collection.

2.4. Procedure

Infants were undressed for data collection. The infant was supported at the trunk by an investigator, and the parent sat in front of the child. The investigator held a small, flat contact switch between the infant and the investigator's hand. Once the infant was stable and calm, the investigator supporting the infant began a verbal count of "1–2–3", and released the trunk support at the count of "2", (thus releasing the contact switch which was used as an event marker for the exact time of

release of trunk support), and data were collected while the child attempted to maintain sitting postural control (Harbourne et al., 1993). The parent, who had previously selected a toy from a standard set of toys, brought the toy into the infant's view when given the verbal cue of "3" during the count, which was immediately after postural support was released, and held the toy within arm's reach of the infant (Fig. 1). Parents were encouraged to smile and give verbal encouragement to the infant to obtain the toy, and present the toy in the same spot each time. If the infant became fussy or tired the data collection was paused for the parent to hold the infant or comfort them, and only resumed when the infant was in a quiet, alert state. Because of individual differences between infants, and the different stages of sitting control depending on infant age, we obtained from 3 to 10 successful reaches for each infant at each visit.

2.5. Data analysis

2.5.1. Behavioral coding

Behavioral coding was done at the Infant Motor Behavior Laboratory at the University of Delaware. Video recordings were reviewed by a coder who was blinded to the purpose of the study. Intra-rater reliability was established at >90% for this coder for 20% of the data using the equation: [agreed/(agreed + disagreed)] × 100 (Angulo-Kinzler & Horn, 2001; Harris & Lahey, 1978; Lobo & Galloway, 2008). The coder used MacSHAPA behavioral coding software to review the videos and code for instances and durations of each behavior. The behaviors coded for were: (A) *hand support*, or when the hand is contacting the infant's lower extremities or the support surface, (B) *toy contact*, or the time and the frequency either or both hands were physically contacting the presented toy (coded for right and left hands and bilateral contacts separately); number of toy contacts were normalized to times per minute, (C) *anterior trunk movement*, or when the trunk makes a large (>15°) flexion movement toward the toy, (D) *posterior trunk movement*, or when the trunk makes a large (>15°) extension movement away from the toy, and (E) *hands on assistance*, or when the experimenter guarding the infant has her hand in contact with the infant's leg, trunk, or other part of the body Custom programming by one of the authors in Filemaker Pro (Filemaker, Inc., Santa Clara, CA) was used to compile and analyze these data.

2.5.2. Kinematics

All kinematics were measured relative to the time of the infant's reach. Displacement of the wrist marker was noted from the beginning to the end of the reach. Initiation and end of reach was determined by a frame-by-frame analysis of the VICON marker data, the accompanying videotape to verify the overall infant behavior (excluding movements that were not directed toward touching or obtaining the toy and only including successful reaches where the toy was touched or grasped), and the displacement data from the wrist marker (Thelen, Corbetta & Spencer, 1996). Overall, at stage 1 sitting 70% of the trials were unsuccessful; at stage two 30% were unsuccessful, and at stage 3 all reaches were successful. A valid reach meant that the infant did not have sitting support, which was indicated by the event marker producing an analog signal that denoted the moment of release of trunk support. The beginning of reach frame and the end of reach frame demarcated the video segments of interest for trunk and pelvis angle data, as well as the time of reach initiation and end of reach to measure of the EMG onsets.

Trunk angle and *pelvic angle* were determined from kinematics and represent the anterior–posterior angle of the respective body segments in the sagittal plane at the end of a reach. Trunk angle was determined from the angle formed from the C7 marker, to the lumbar marker, to the marker placed at the hip joint (Harbourne et al., 1993). Thus, the variable "trunk angle" represented the curvature of the infants back in the sagittal plane as the infant completed the reach (Fig. 1). The pelvic angle was determined from the angle formed from the lumbar marker, to the marker at the hip joint, to the ankle marker. During this stage of development the infant's legs are maximally externally rotated, forming a wide circle sit position during data collection. Because the legs remained in contact with the floor (see Fig. 1), and the angles were in the sagittal plane, this was the most reliable way of measuring pelvic anterior/posterior alignment. The variable "pelvic angle" represented the movement of the axial portion of the body forward via the pelvis, in the sagittal plane at the completion of the reach.

Angles were calculated with VICON software at the end of the reach, when the infant's hand touched the presented object. The available trials for each child were averaged for that month's session. These averaged values reflect the position of the trunk and pelvis in the sagittal plane at the end of a successful reach.

2.5.3. EMG

The EMG data were analyzed by visual inspection to determine which muscles were active immediately prior to and during the reach, and their order of activation. We wanted to determine postural responses of the trunk and leg muscles related to the initiation of reach. Reach was defined by the above detailed kinematic criteria. Visual inspection was done for both the raw EMG data and rectified signals. Muscle onset was determined when activity of the muscle was approximately 50% above the baseline activity level for greater than 100-ms, and within ±200-ms of the initiation of reach (Harbourne et al., 1993). Baseline was the level of EMG sampled for a 200-ms period prior to the initiation of any muscle burst related to the reach, for each muscle and for each trial. Twenty percent of the sample was analyzed twice by the same rater, with a resulting 90% agreement for order of muscle onsets between the two measurement samples indicating good reliability. The order of the muscle onsets within the identified time period of the reach was documented as a muscle synergy, and totaled for frequency of occurrence for each stage of sitting for each infant. All trials for each infant in which a reach was present,

and there was an identifiable sequence of muscle activation as described above, were analyzed and included in the group summary.

2.6. Statistical analysis

All statistical analysis was performed with SPSS software (Version 13.0). The alpha level was set at 0.05. A repeated measures analysis of variance was performed, with post hoc pairwise comparisons. Long-term effects were examined using a general linear model (GLM) repeated-measures procedure for each dependent variable with time (stages 1, 2 and 3) as the within-subject variable. Significant findings were followed by post hoc analysis using Fisher's least significant difference (LSD) approach. Adjustments for multiple comparisons were not made because of the potential for increasing Type II error with this small sample (Perneger, 1998; Rothman, 1990).

3. Results

3.1. Behavioral coding

The results to follow do not appear to be due to differences in assessment duration or amount of investigator assistance across phases. Specifically, the duration of time infants were assessed was not significantly different across the 3 phases of sitting (mean 3.03 ± 0.49 min per sitting stage). Nonetheless, we normalized all behavioral data with respect to the assessment time at each stage of sitting. Furthermore, there were no significant differences across sitting phases in the amount of time the investigator provided hands-on assistance ($7.9 \pm 3.8\%$ of the total assessment time). The consistency of hands-on assistance was due to the careful orchestration of the experimental procedure, in which the person assisting the infant maintained their hands on the infant's trunk until a verbal count of two, at which time the infant was released from support. At the count of three, the toy was brought into the visual and reach field of the infant, and the infant was free to reach, explore, fall (into the arms of the assistant) or just sit and look. If the experimenter had to assist the infant because of falling, the trial was ended. Thus, the amount of assistance time per trial did not vary depending on the skill of the infant.

3.2. Hand use for support and reaching

Across developmental time and sitting phases, infants transitioned from using their hands for support to increasingly freeing them to explore a toy. They often explored with both hands at the same time, allowing for more sophisticated object exploration and information gathering (Fig. 3). However, even when they were classified as independent sitters, infants used their hands at times for postural support during a reach. Thus, there were trials when the arms served dual purposes: providing support, but also freed for two-handed reaching. The percent of time infants used their hands to interact with a toy, rather than for support, in sitting increased across the 3 stages of sitting. A small percent of other behaviors (for example, hands on their own body, not necessarily in a supportive role) also occurred, but were not counted in this report. Infants spent more time (middle bars, Fig. 3) with either or both hands in contact with the toy as they progressed through the stages of sitting (stage 1 to stage 2: $F = 5.97$, $P = 0.05$; stage 1 to stage 3: $F = 43.76$, $P = 0.001$). They also improved their ability to free both hands to interact with the toy as they progressed through the stages of sitting (left bars, Fig. 3). They had significantly more instances of contacting the toy with both hands (stage 1 to stage 2: $F = 7.125$, $P = 0.04$; stage 2 to stage 3: $F = 17.957$, $P = 0.008$). Means and standard deviations for frequency of bilateral toy contacts (normalized per minute) were: stage 1 = 0.48 (0.75); stage 2 = 3.18 (2.97); and stage 3 = 2.64 (1.30). Bilateral toy contact *time* (right bars, Fig. 3) also increased as sitting became more independent (stage 1 to stage 2: $f = 5.613$, $p = 0.06$; stage 1 to stage 3: $F = 6.691$, $P = 0.04$).

3.3. Trunk movement during sitting and reaching

Behaviorally, the number of trunk movements was significantly less in stages 1 and 3 sitting than in stage 2 (see Figs. 2 and 4). Infants had more anterior trunk movement in stage 2 sitting than in stages 1 or 3 (stage 1 to stage 2: $F = 7.863$, $P = 0.04$; stage 2 to stage 3: $F = 8.691$, $P = 0.03$). They also had more posterior trunk movement in stage 2 sitting than in stages 1 or 3 (stage 1 to stage 3: $F = 10.132$, $P = 0.02$; stage 2 to stage 3: $F = 11.01$, $P = 0.02$). Therefore, infants displayed the least amount of trunk movement during early sitting and during their most mature sitting.

3.4. Falling

By definition, infants did not fall during stage 3 sitting while reaching. Therefore, only stage 1 and stage 2 were compared for falls during the reach. Falls forward, backward, and sideways were counted as a fall. The average percent of trials with falls in stage 1 were 9%, and in stage 2 were 53%. There was a significant difference between stages ($t = -6.39$, $P = 0.00$), with a greater number of falls occurring during stage 2 sitting.
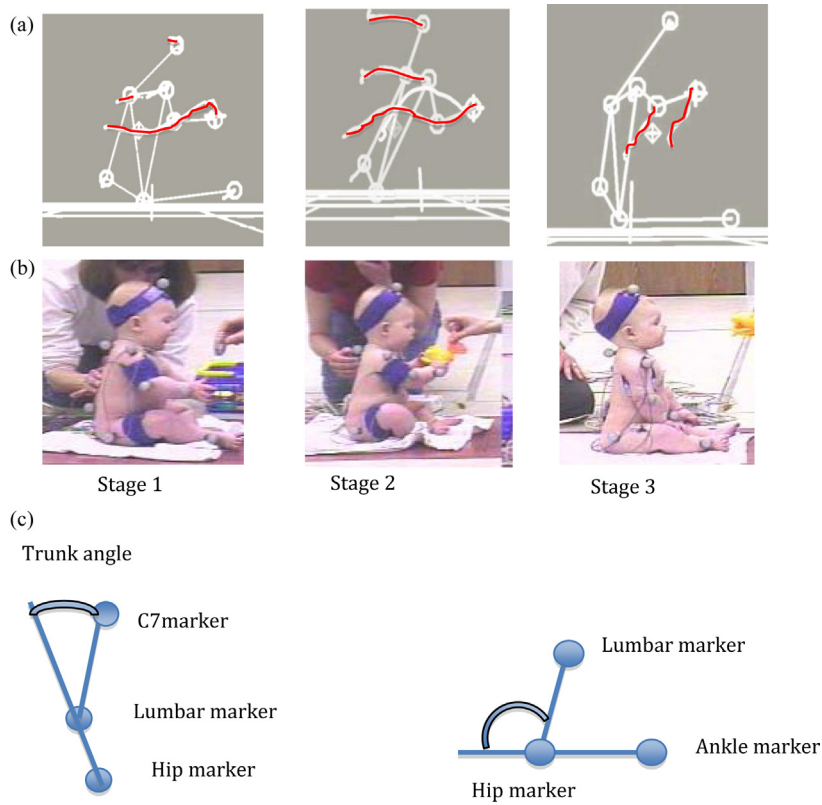
Fig. 2. (a) VICON stick figure of infant constructed from joint markers. Graphic depiction of reach kinematics at stage 1, stage 2 and stage 3 of sitting. Curved lines (in red) from circular markers show the marker paths during a single reach, with the hand marker having the most movement. Stage 2 (middle picture) displays movement of the trunk and pelvis as well as the hand movement. (b) Single frames of the video of one child at stage 1, stage 2 and stage 3 of sitting; note the inconsistent placement of the head marker, resulting in invalid kinematic data for the head. (c) Angle calculation (indicated by arcs) for the trunk angle and the pelvic angle. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)
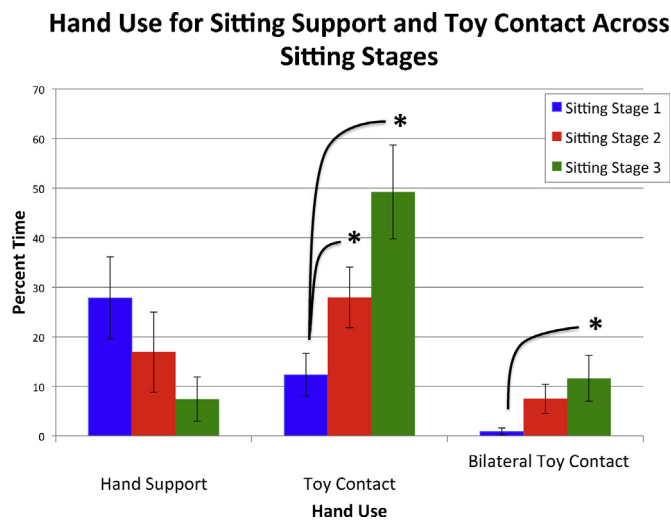

Fig. 3. Changes in hand use for support or to contact a toy as infants progressed through the three stages of sitting. Infants used their hands less for support (left bars) and more for object interaction (middle bars indicate either hand touching object). They also increased bilateral hand–toy contacts across time. $^{*}P \leq 0.05$ (right bars).
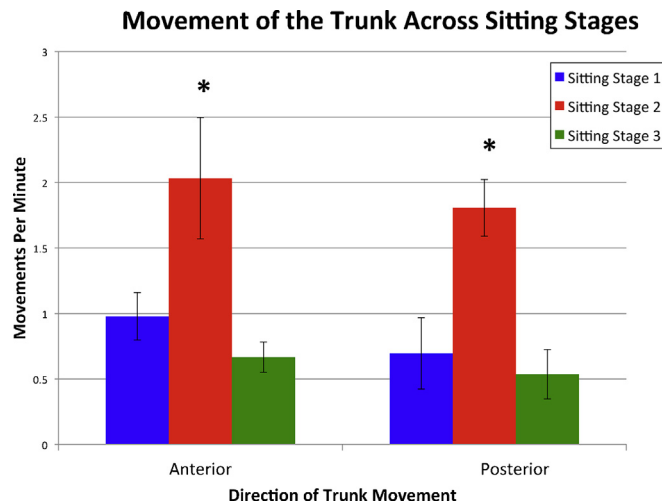
Fig. 4. Movement of the trunk across the three stages of sitting. Infants had more trunk movements in both directions in stage 2 of sitting than in stages 1 or 3. $^*P \leq 0.05$.

3.5. Kinematics

Trunk angle decreased significantly from stage 1 to stage 3 ($F = 4.933$, $P = 0.020$). Post hoc testing revealed a significant difference between stages 1 (84.8°) and 3 (69.2°) ($P = 0.032$); but not between stages 1 and stage 2 (76.4°) ($P = 0.076$), or between stages 2 and 3 ($P = 0.13$). Pelvic angle was less in stages 1 (92.8°) and 3 (91.3°) than in stage 2 (99.3°). There was a significant difference only between stages 2 and 3 ($F = 4.565$, $P = 0.05$). See Fig. 2c for graphic of angle measurements.

3.6. EMG

Table 1 describes EMG for each subject during each stage of sitting. The table lists the percent of trials that included muscle onsets of the trunk only, the trunk and leg muscles in combination, or only the leg muscles. The table also lists the percent of trials in which reach occurred prior to postural muscle onsets, or after postural muscle onsets. If the pattern of muscle onsets occurred in only 1 trial, that is indicated by a (1).

Stage 1: EMG was characterized by multiple and varied muscle onsets, tonic muscle activity, and unclear onset of muscle bursts (see Fig. 5). Trunk and leg muscles became active within 200 ms of the onset of reach but in multiple patterns, both before and after reach onset. Trunk and leg muscle synergies were present in 52% of trials, compared to 43% of trials with just leg muscle onsets related to the reach, and 4% of trials exhibiting just a trunk extensor onset.

Overall, in 54% of trials the reach onset occurred prior to any postural muscle activity, with 45% of trials exhibiting postural muscle onsets prior to the reach. Lower extremity muscle onsets (hamstrings or quadriceps) were timed most tightly to the onset of biceps activity 69% of the trials, as opposed to the trunk extensors, which were linked tightly to the biceps 31% of the trials.

Stage 2: During this stage of sitting, muscle onsets were more distinct, but high variability continued. Increased trunk extensor onsets were apparent, with 25% of trials showing just a trunk extensor muscle burst in relation to the reach, 58% of trials using both trunk and leg muscles, and 16% of trials using just leg musculature.

The percentage of trials during which postural activity occurred prior to the reach increased to 56%, as opposed to reach onset prior to postural activity 44% of the time. The trunk extensors were now more closely linked to the onset of biceps activity and reaching, with 62% of the trials showing a linkage of trunk extensor/biceps vs. 38% of trials showing a linkage between the leg muscles and the biceps.

Stage 3: At this independent stage of sitting, the leg muscle onsets were increasingly associated with the reach, although there was still a great deal of variability in the order of muscle activation. Trunk and leg muscle onsets together were related to the reach onset for 46% of trials, only leg muscle onsets were related to the reach onset for 36% of trials, and just trunk extensor onset for 17% of trials.

Reach onset occurred 77% of the trials after postural muscles activated, and only 23% of the trials prior to postural muscle onsets. Lower extremity muscle onsets were more closely associated with the biceps onset at 73% of trials, and the trunk extensor onset only at 27% of trials. Of the lower extremity muscles, the hamstring group was more often linked closely to the onset of biceps activity at 40% of all trials, and the quadriceps was most closely linked for 33% of trials.

There was a significant increase in the percent of trials where infants activated postural muscles prior to their reach vs. after their reach between the 3 stages of sitting ($F = 3.18$, $P = 0.05$). Post hoc tests revealed a significant difference between stages 1 and 3 ($P = 0.01$), yet no significant difference between stages 1 and 2 nor between 2 and 3.

Table 1
EMG muscle pattern occurrences. (1) indicates occurrence in only 1 trial.

Subject	Sitting Stage	Tonic	Only trunk	Trunk and leg	Only Leg	Reach prior to postural ms	Reach after postural ms
1	1			50% (1)	50% (1)	50% (1)	50% (1)
2	1			100% (1)		100% (1)	
3	1				100% (1)		100% (1)
4	1		33% (1)	33% (1)	33% (1)	33%	66%
5	1			50% (1)	50% (1)	66%	33%
6	1	100%				-	-
7	1			100%		66%	33%
8	1	No data				-	-
9	1			33%	66%	66%	33%
Avg	1		**4%**	**52%**	**43%**	**54%**	**45%**
1	2		100% (1)			100% (1)	
2	2			100%			100%
3	2			100%			100%
4	2			100%		50%	50%
5	2			100% (1)			100% (1)
6	2		100%			100% (1)	
7	2			66%	33%	50%	50%
8	2	No data				-	-
9	2				100%	50%	50%
Avg	2		**25%**	**58%**	**16%**	**44%**	**56%**
1	3		33%	66%			100%
2	3			75%	25%		100%
3	3		33%	33%	33%		100%
4	3		20%	60%	20%	20%	80%
5	3			66%	33%	66%	33%
6	3			50%	50%		100%
7	3			33%	66%	40%	60%
8	3		66%	33%		33%	66%
9	3				100%	50%	50%
Avg	3		**17%**	**46%**	**36%**	**23%**	**77%**

The two columns shaded on the right indicate reach occurrence related to postural muscle activation.

4. Discussion

The results of this study, in part, extend the findings of previous studies of infant sitting and reaching. Five findings advance our knowledge of how sitting and reaching emerge together in infancy, and will be discussed here.

1. Reaching successfully when learning to sit, as measured by toy contacts, increases over time as sitting develops. This linear improvement in contacting objects as infants progressed through three stages of sitting indicates that reaching is not necessarily perturbed during the most unstable stage of sitting, stage 2.
2. In spite of falling and/or significant trunk and pelvis movement in stage 2 sitting, infants persist in reaching, and continue to increase their reaching attempts.
3. Infants gradually straighten their trunk over time as they learn to sit independently and reach. This change in trunk alignment does not occur separately from reaching, but is integrated with the reach/exploration behavior, contributing to the coordination of eyes, head, and hands.
4. Prospective control of the trunk and pelvis for the upcoming sitting–reaching combination increases over developmental time as reflected in gradual emergence of an EMG activation sequence of pelvic and trunk muscles activating to stabilize the body prior to arm muscle activation and reach.
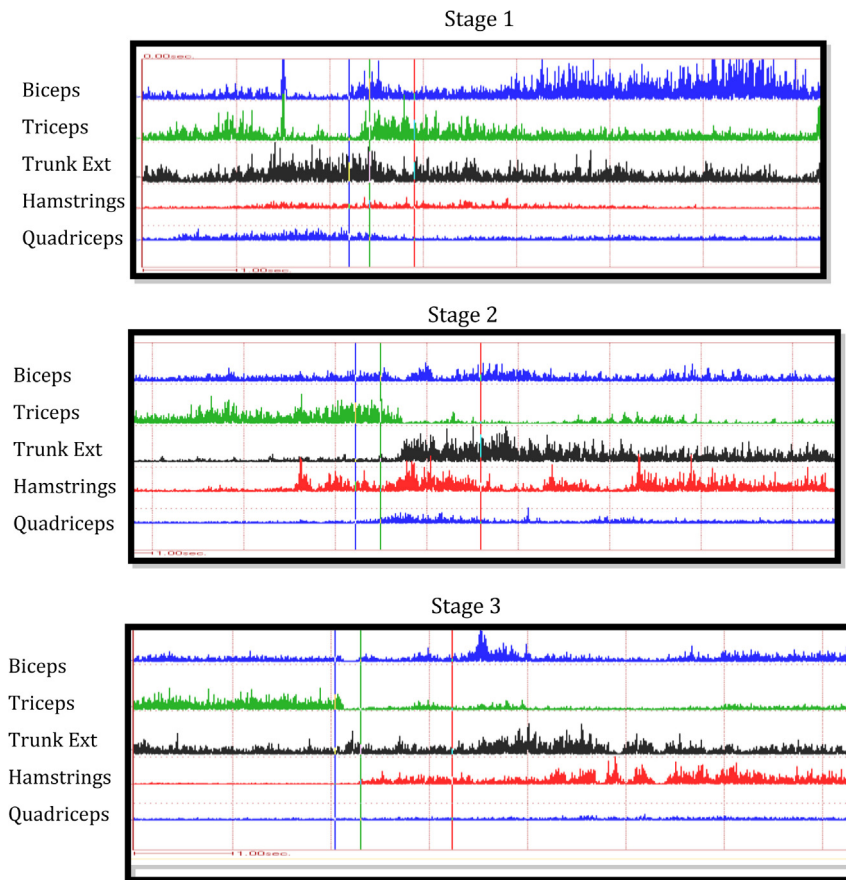
Fig. 5. Sample EMG for the biceps, triceps, trunk extensor, hamstrings and quadriceps muscles at stage 1, stage 2 and stage 3 of sitting, during reach. EMG is rectified but unfiltered. The first vertical line marks 200 ms prior to start of reach; the second vertical line is the start of movement for the reach; and the third vertical line is the end of reach. *Stage 1*: Note the co-activation of biceps and triceps, with no activation of the other muscles related to the reach onset. *Stage 2*: Note the triceps turns off late in the reach, and the trunk, hamstrings and quadriceps muscles turn on near the reach, but either late or early. *Stage 3*: Biceps and triceps tightly timed so the biceps activates and the triceps turns off at reach onset, the trunk extensors burst just prior to reach initiation and stay on, and the hamstrings activate in conjunction with the biceps.

5. Reaching is not significantly perturbed by the emergence of sitting. In contrast, sitting development may be constrained by and likely driven, at least in part, by infants' significant interest in reaching for objects.

    In our first hypothesis, we predicted that reaching would show a nonlinear progression reflecting a significant disruption in reaching attempts as sitting emerged. That is, postural instability, risk of falling and/or cognitive load of planning balance and the dual use of the arms would significantly disrupt the ongoing progression of reaching. This hypothesis was clearly not supported. We found, on the contrary, that infants persistently and successfully reached in spite of falls (falls in 53% of trials during stage 2 sitting), disorganized muscle onsets (sometimes activating only trunk muscles, sometimes only leg muscles, and at times both trunk and leg muscles, Table 1) and erratic trunk movement (Fig. 4). Far from disturbing the development of reaching, instability and errors in maintaining sitting balance appear to contribute to further success in achieving infants' goal of interacting with the world through successful reaches. Similar to findings that reaching improves over developmental time in studies in which infants were supported in a seat (Fetters & Todd, 1987; Thelen et al., 1993), we found reaching steadily improves when infants are *not* supported by a seat. In addition, we were able to determine that, in unsupported sitting, infants decrease the amount of time that arms are used for postural support as sitting advances and reaching improves (Thelen & Spencer, 1998). This change in arm use, from a postural support to increasing object manipulation, agrees with past research on developing reach (Spencer et al., 2000; Rochat, 1992) in which the infants were protected from a loss of postural control.

    In spite of failures of postural control, and/or excessive trunk and pelvis movement, infants keep reaching. That is, a loss of balance during a reach does not usually deter an infant from continuing the reach at that moment, or in future attempts. Sitting posture, as measured behaviorally or kinematically, displays instability during stage 2 sitting, when infants begin to control the trunk and pelvis without hand support. Moreover, infants actually experience falls concurrent with reaching during this stage of sitting. Both in terms of immediate, real time attempts, and across developmental time, infants persist in

reaching even when trunk and pelvis instability threatens a fall. This contributes positively to development, because if a loss of balance deterred an infant from reaching, or doing any developmental task, many skills would go unlearned. However, the question may be asked, "Why do infants continue to try?"

This persistence in "trying" importantly occurs across skills in development. Grzyb et al. (2011) suggest that success, in spite of errors, gives the infants an increased sense of control, which is highly rewarding. Although Grzyh et al. did not specify reaching or sitting as the skills to be mastered, they focus on the goal in the mind of the infant. If, for example, the goal of the infant is to socially engage with the parent by interacting and grabbing the presented toy, falling (an error in the experimenter's mind), would be easily ignored as long as proximity to the toy or social engagement was attained. The persistence of the reach behavior in spite of falls in the present study may also reflect infants' understanding of the degree of safety provided by nearby adults and the surrounding environment, and a general awareness of the social net consistently supporting their function. Alternatively, infants at this age may not be upset by small and fast postural disruptions, because they are not yet accustomed to a consistently stable vertical posture. During a related skill, early walking, infants learning to walk incur inconsequential falls an average of 15 times per hour (Adolph, 2008). Obviously, the falls during early attempts at sitting and walking do not deter learning. In fact, the variability and flexibility of the body's configuration within the overall scheme of the task allows the child to create online solutions to motor problems, not all of which succeed in accomplishing the immediate goal of reaching, exploring, or mobilizing. It appears that the goal to contact, obtain and explore objects may take priority, or supersede the need to maintain an upright sitting posture in the moment.

The prioritization of postural stability over reaching success, our initial prediction, was not supported. The results of the current study conflict with previous findings that infants are aware of their postural capabilities and do not attempt to reach unless stabilized (Rochat, Goubet, & Senders, 1999). The differing results between research findings may be due to differing characteristics of the infants in the current study, or different ages and experience in the sitting position. Alternatively, the perspective of the researchers driving both the experimental paradigm and the interpretation of results may differ. That is, a nativistic perspective would support the assumption that young infants innately have self-knowledge of their own ability to reach when learning to sit, and thus would avoid falls. Alternatively, taking a systems perspective supports a different interpretation. As in Thelen et al.'s (1993) longitudinal study of reaching development, our data support the emergence of postural control in sitting and ongoing reaching skill in infancy as skills both "under construction". As such, infants learn to solve the problem of investigating the world and interacting with people and objects, together with managing their body within the task. As Adolph and Eppler (1998) suggest, infants must learn to control posture in different positions, and this learning of a postural "set" requires not only the passage of time, but also multiple experiences, practice, and errors that occur as a child engages in activity within each posture (sitting, crawling, standing). However, the simplest argument for why our results do not support the primacy of postural stability over reaching success as previous studies suggest, is that previous paradigms have not allowed infants to be independently sitting, even though sitting may be tenuous. The environmental support provided by previous studies likely produced different behaviors than our study, which did not utilize postural supports.

Our results support the presumption that the trunk gradually straightens over time in a linear manner as infants learn to sit independently and reach. The trend of trunk straightening showed statistical significance only between stages 1 and 3 sitting, and not between stages 1 and 2, in agreement with previous kinematic analysis (Harbourne et al., 1993). The lack of significant difference between stage 2 sitting and earlier or later sitting stages likely reflects, at least in part, that during stage 2 sitting infants still partially used their arms for sitting support, which would position the trunk in a more curved posture. In addition, a general straightening of the infant's trunk over time has been noted in descriptive studies (McGraw, 1939); however, previous studies did not link the straightening alignment to the function of reaching as we have shown here. The finding of trunk curvature in stage 2 (that is not significantly different from stage 1) may also reflect the movement of the pelvis forward in conjunction with the reaching arm during stage 2 of sitting (see Fig. 2). During stage 1 and stage 3 the reach was primarily done with arm movement rather than a combination of forward trunk movement (as noted in Harbourne, Karst, & Tyler, 2001) and arm movement. Thus, it appears that infants do not just change trunk alignment in isolation, but do so within the ongoing exploration and investigation of their body's abilities within the world. The trunk straightens to support the emerging skill of object manipulation by bringing the body supporting the head, stable hands and vision together in a coordinated manner.

EMG revealed variable muscle onsets both between infants and within each infant (Table 1). Over time, infants increasingly activated trunk and leg muscles together and did so prior to the start of a reach. This may indicate an emerging ability to prospectively control the trunk and pelvis for the upcoming sitting–reaching combination. Previous studies report similar results regarding infants' muscle activation early in the development of sitting (Harbourne et al., 1993; Hadders-Algra et al., 1996a). This information, in combination with our behavioral and kinematic results, indicates that infants are gradually assembling, over time, muscle linkages which prove to be increasingly successful over time.

Based on our findings in this study, reaching is not perturbed by sitting development; but rather, sitting development is perturbed by and possibly driven by the infant's interest in reaching to obtain objects in the environment. Perhaps the primacy of the head and hands as investigative organs relegates trunk and pelvis control to a secondary role during this time period of development. Thus, the drive to reach and obtain objects primarily directs head and hands, and postural control gradually assembles to optimally support functional reaching. Although the behavior of reaching for objects has been described as originating at 4 months of age, in actuality the infant has been making reaching movements since birth (Van der Meer, 1997). Even though these early "reaches" are slow, awkward, and many times unsuccessful, the infant begins

to coordinate the head (vision) and movement of the hand quite early in development (Butterworth & Hopkins, 1998; Bower, Broughton, & Moore, 1970). The reaching described at 4–5 months of age emerges as the infant begins to understand and manage gravitational forces and reactive forces on the arm and hand. As this is the time when sitting is emerging, reaching and sitting must co-emerge for functional exploration and manipulation of the environment.

4.1. Limitations

There were several limitations to this study. The small number of infants in the study limits our ability to generalize the findings. Because we wanted to have the infants reach during data collection, we varied the toys presented to the infant to make sure we obtained reaches and did not bore the infant by presenting the same toy repeatedly. The variability of toys presented may have had an effect on the configuration of the hand and arm during the reach.

4.2. Conclusions

Infants appear to prioritize the capture and investigation of an object presented to them in spite of postural errors that may threaten vertical posture in sitting. The study of early learning can be strengthened by blending the detailed examination of the emergence of motor skills and infant adaptation to environmental opportunities and obstacles within a natural social context.

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