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Temporal-spatial reach parameters derived from inertial sensors correlate to neurodevelopment in toddlers born preterm

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ABSTRACT

Temporal-spatial reach parameters are revealing of upper-limb function in children with motor impairments, but have not been quantified in a toddler population. This work quantitatively characterizes temporal-spatial reach in typically-developing (TD) and very-low-birth-weight (VLBW) preterm toddlers, who are at increased risk of motor impairment. 47 children born VLBW (<1500 g birth-weight; ≤32 weeks gestation) and 22 TD children completed a reaching assessment at 18–22 months of age, adjusted for prematurity. Inertial sensors containing accelerometers, gyroscopes and magnetometers were fixed to toddlers' wrists while they reached for a cube. Reach time, path length, velocity at contact, peak velocity magnitude and timing, acceleration at contact, and peak acceleration were derived from inertial-sensor and high-speed video data. Preterm children also received the Bayley Scales of Infant Development—3rd Edition (BSID-III). Compared to TD toddlers, preterm toddlers had significantly different reach path length, velocity at contact, peak velocity magnitude and timing, acceleration at contact, and peak acceleration. Among preterm toddlers, decreased reach time (rho = −.346, p = .018), decreased time to peak velocity (r = −.390, p = .007), and increased peak acceleration (r = .298, p = .044) correlated to higher BSID-III fine motor scores. Toddlers with below-average fine motor scores had significantly higher peak and contact velocity. Preterm toddlers demonstrated substantial differences in temporal-spatial reach parameters compared to TD toddlers, and evidence indicated several reach parameters were revealing of function and may be useful as a clinical assessment.

1. Introduction

Children born preterm account for 11% of births in the US (Martin et al., 2015) and are disproportionately affected by cerebral palsy (CP) and other neurodevelopmental impairments. Children born preterm with very-low-birth-weights (≤1500 g) develop CP at a rate of 10–15%, compared to 0.3% of children born full term. An additional 40% may present with developmental coordination disorder (DCD), a rate three to four times higher than the general population (Vohr et al., 2005; Williams et al., 2010).

Children with CP and DCD often have impaired upper-extremity function, thus, children born preterm with very-low-birth-weight are at increased risk for functional impairment in the upper extremities. Early identification is essential for early, more effective treatment. These impairments can be quantified by measuring the temporal-spatial parameters of reaching, which is a well-practiced functional task used in feeding, grooming, and otherwise interacting with the world during daily life. Children with CP tend to have longer reach times, less efficient paths to the target object, higher velocities at contact with the target object, and later peak velocities than their typically-developing peers (Butler et al., 2010; Chang et al., 2005; Rönnqvist and Rösblad, 2007; van der Heide et al., 2005). While the literature on reaching in children with DCD is less extensive, to date they have been found to demonstrate longer times to complete a movement and altered timing of peak velocity (Johnston et al., 2002; Smyth et al., 2010). Identifying and quantifying reach impairment is valuable because treatments aimed at improving functional reaching have successfully helped children decrease movement time and improve path efficiency (Fetters and Kluzik, 1996; Kluzik et al., 1990).

While temporal-spatial reach parameters and their functional significance have been quantified in the general pediatric population, they have not been explored at toddler-age. Clinically, assessments of toddler upper-extremity function rely primarily on

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assessments of tone, posture, reflexes and milestone achievement during routine standard-of-care visits (O'Shea, 2008). Other assessments include the Bayley Scales of Infant Development—3rd Edition (BSID-III) which is in common clinical use for high-risk toddler-aged children. The BSID-III offers a fine motor assessment, in which a trained psychological examiner coaxes the child to complete tasks such as placing blocks in a cup. Although the BSID-III is well-validated, it is expensive, long (the full test is about 90 min for toddlers aged 18–22 months), and often subjective (Bayley, 2006; Connolly et al., 2012). Due to the expense, time, and difficulty in finding enough qualified examiners, BSID-III assessments are often limited to the most high-risk children. An assessment using inertial sensors offers two advantages: firstly, objective measures of function; and secondly, an easier, portable, more affordable test which can thus be clinically applied to—and thus potential benefit—a higher proportion of at-risk children. However, before such an assessment can be applied clinically, it must be determined whether quantitative measures of reach in a toddler population will be revealing of motor function. This work quantitatively characterizes reach in both typically-developing (TD) and VLBW preterm age-matched toddlers, to (i) provide a baseline of typical reach at 18–22 months of age and (ii) to explore whether temporal-spatial reach parameters are related to motor function for this age and population, and thus could be clinically useful.

The validity of inertial sensor methods in quantifying adult and toddler reach was previously shown by our group (Cahill-Rowley and Rose, 2017). This work applies those methods to quantitatively characterize reach in both TD and VLBW preterm children at 18–22 months of age, adjusted for prematurity, in relation to neurodevelopment assessed using BSID-III. Temporal-spatial reach parameters are measured with inertial sensors and reported for TD and preterm toddlers, as well as for subgroups of preterm toddlers who performed better ($\geq$8) or worse (<8) on the BSID-III fine motor section. Relationships between reach parameters and neurodevelopmental function in preterm toddlers are explored. It was hypothesized that (i) reach parameters would be significantly different between TD toddlers and VLBW preterm toddlers, and that (ii) reach parameters of preterm children would correlate with upper-limb function, as measured by BSID-III fine motor scores.

2. Methods

2.1. Participants

Children born preterm ($\leq$32 weeks gestational age) with very-low birth-weight (VLBW) were recruited in infancy from Lucile Packard Children's Hospital at Stanford in 2010 and 2011 in a longitudinal study of neonatal neural correlates of neurodevelopment in preterm children (Rose et al., 2015). Infants with evidence of genetic disorders or congenital brain abnormalities were excluded. This inclusion criteria was adopted from the Neonatal Research Network (Hintz et al., 2005). Children received follow-up neurodevelopmental evaluation and reach assessment at 18–22 months adjusted age; 46 children successfully completed both assessments, and one child completed the reach assessment but not the neurodevelopmental evaluation. TD children aged 18–22 months who were born full-term were recruited from the community with IRB-approved advertisements; 22 children successfully completed the evaluation. All ages reported in this study were adjusted for prematurity, where prematurity existed. Consent was obtained from at least one parent or legal guardian of each child for this IRB-approved study.

2.2. Performing the reaches

Inertial sensors with three-axis accelerometers, gyroscopes, and magnetometers (APDM, Inc., Portland, OR) were fixed to toddlers' wrists. The sensors measure $48.5 \times 36.5 \times 13.5$ mm and weigh 22 g; for comparison, a sensor is about the width of two dimes and the weight of a AA battery. Previously, weights of 56 g—more than double the weight in the present study—did not affect reaching velocity of children aged 18 months (Van der Fits et al., 1999). Each toddler was seated in a highchair, facing the investigator across a table. A parent or guardian sat directly behind their child. After a warm-up period, during which the investigator established a rapport of giving, taking, and returning small toys across the table with the toddler, the reaching session began. The parent placed their child's hands in the starting position, palm-down on the edge of the table with elbows bent comfortably at approximately 90°; the parent cupped their hands over their child's, restricting the child's movement until cued to release and allow the child to reach. At the same time the child's hands were released an attractive cube was revealed by pulling away a clipboard. The placement of the cube was marked by a piece of tape on the table, on a spot located at midline and at approximately 75% of the child's maximum reach. The cube was a standard red BSID-III cube decorated with child-themed stickers. To maintain attention to the task, other objects were occasionally revealed behind the clipboard instead, and breaks or crackers were employed as needed.

A reach was considered usable if the child was interested in picking up and inspecting the cube with one hand, and made a good effort to obtain it. For example, poking the cube, pushing it away, or picking it up only to throw it without looking at it first did not qualify as usable. If the child "pounced," on the cube, showing more interest in catching or smacking it as quickly as possible without looking at it, that reach did not qualify and was not used. Picking it up to show a parent demonstrated interest and was usually usable. Pauses only disqualified a reach if they appeared to be the result of distraction; otherwise, they were included as they may reflect impaired motor planning or control. Reaches were disqualified if the parent was still touching the child when he or she initiated movement. Reaches were also disqualified for poor start positions, or if the hands were not approximately still when the reach was initiated.

2.3. Temporal-spatial reach parameters

Reach time, path length, velocity at contact, peak velocity magnitude and timing, acceleration at contact, and peak acceleration were derived from inertial-sensor acceleration and high-speed video data as described previously in the companion to this paper, a validation study of temporal-spatial reach parameters derived from inertial sensors compared to 3D marker-based motion capture (Cahill-Rowley and Rose, 2017). Briefly, the child reached with an inertial sensor fixed to the wrist with an elastic Velcro band. The entire testing session was recorded with high speed video; a third sensor, synchronized to the ones on the child's wrists, was struck with a pen tip recorded by video and sensor data, allowing synchronization between the measures. Reach initiation and object contact were manually identified via frame-by-frame inspection of high-speed video (239.76 frames/s) (Casio Computer Co., LTD, Dover, NJ), and the corresponding data extracted from the sensors. Sensor data were recorded at 128 Hz. Velocity of the wrist throughout a reach was calculated using numeric integration; the effect of sensor drift was mitigated using a null-velocity assumption at start for a short duration (timescale on the order of 1 s), as described previously in the companion methods publication (Cahill-Rowley and Rose, 2017). Position data were likewise calculated from double numeric integration, again possible because of the null-velocity start and short timescale. All temporal-spatial parameters in the present study were accurate compared to concurrent measures made with 3D marker-based motion capture methods, with an average intraclass correlation coefficient of