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Practice and Proficiency: Factors that Facilitate Infant Walking Skill

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Abstract

Infant walking skill improves with practice—crudely estimated by elapsed time since walk onset. However, despite the robust relation between elapsed time (months walking) and skill, practice is likely constrained and facilitated by infants' home environments, sociodemographic influences, and spontaneous activity. Individual pathways are tremendously diverse in the timing of walk onset and the trajectory of improvement, and presumably, in the amount and type of practice. So, what factors affect the development of walking skill? We examined the role of months walking, walk onset age, spontaneous locomotor activity, body dimensions, and environmental factors on the development of walking skill in two sociodemographically distinct samples (*n*s = 38 and 44) of 13-, 15-, and 19-month-old infants. Months walking best predicted how well infants walked, but environmental factors and spontaneous activity explained additional variance in walking skill. Specifically, less crowded homes, a larger percentage of time in spontaneous walking, and a smaller percentage of short walking bouts predicted more mature walking. Walk onset age differed by sample but did not affect walking skill. Findings indicate that elapsed time since walk onset remains a robust predictor of walking skill, but environmental factors and spontaneous activity also contribute to infants' practice, thereby affecting walking skill.

Keywords

infant; walking; locomotion; early experience; motor

The Development of Walking Skill

Improvements in walking skill make infants' movements more efficient and coordinated. Increases in leg strength, balance control, and inter- and intralimb coordination enable infants to walk more quickly and fluently across uniform ground (Breniere, Bril, & Fontaine, 1989; Hallemans, De Clercq, Van Dongen, & Aerts, 2006; Ivanenko, Dominici,

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& Lacquaniti, 2007; Shumway-Cook & Woollacott, 2017; Thelen, 1984). Moreover, improvements in walking skill facilitate navigation in real-world situations such as walking safely across a slippery floor, descending a small stair, stepping over a toy, or steering around furniture. Walking skill supports such adaptive, functional behaviors by allowing infants to modify the length, width, and speed of their steps to accommodate variations in the terrain. Indeed, skilled infants can take steps longer than their leg length to race over flat ground (Badaly & Adolph, 2008), and they can take tiny steps to break forward momentum to walk down steep slopes (Gill, Adolph, & Vereijken, 2009).

A century of research shows that walking skill improves as infants accrue practice with walking (for reviews, see Adolph & Robinson, 2013, 2015; Bril & Ledebt, 1998). When infants first begin walking, their steps are so short that the side-to-side distance between steps often exceeds the front-to-back distance (Adolph, Vereijken, & Shrout, 2003; Bril & Breniere, 1992). Over weeks of walking, infants' steps become longer, narrower, and faster. Generally, improvements are most rapid in the first three to four months after walk onset and more gradual thereafter (Adolph et al., 2003; Ledebt & Bril, 2000).

Elapsed Time Walking as a Proxy for Practice

The amount of elapsed time (number of days, weeks, or months) since walk onset is widely used as an approximation of infants' accumulated practice with walking (Adolph & Robinson, 2013, 2015). Time walking strongly predicts improvements in infants' walking skill, even more so than infants' test age or their body dimensions (Adolph et al., 2003). But prediction is not explanation (Adolph & Berger, 2006). Although elapsed time walking is typically referred to as "walking experience," conceptually, time since walk onset is more akin to infants' "walking age" than to their accumulated practice (Clark, 2005). Similarly, across developmental domains, test age is a strong predictor of improvement, but age cannot explain developmental improvements (Wohlwill, 1970). Simply put, elapsed time since walk onset no better characterizes infants' walking experience than elapsed time since birth characterizes infants' life experience.

Rather, each infant accumulates a unique set of walking experiences not captured by the mere passage of time. So, counting only elapsed time units—whether days, weeks, or months—is not equivalent to counting infants' steps or their time in motion. After infants can walk, they choose *how* to engage in spontaneous locomotor activity—walking a lot or a little, taking slow or quick steps, stringing together short or long sequences of steps, and so on. Moreover, the age at which infants begin walking varies widely, meaning babies have different brains and bodies when they "start their clocks" and begin their practice regimens. And opportunities to practice walking may be affected by infants' body characteristics, space to move inside and outside the home, and family demographics. Together, these factors—walk onset age, spontaneous locomotor activity, and body, environmental, and sociodemographic factors—likely affect infants' everyday walking practice and thereby improvements in walking skill.

Potential Influences on Practice with Walking

Walk Onset Age—The onset of independent walking spans a large normative age range, from 8 to 18 months (Martorell et al., 2006). But does onset age matter for improvements in walking skill? That is, does one month walking predict the same improvement in walking skill for an 8-month-old as for an 18-month-old? If an earlier walk onset age reflects faster neural-muscular maturation, then infants who begin walking at 8 months might also demonstrate faster improvements in walking skill. Alternatively, later walkers might have an advantage. Infants who begin walking at 18 months are presumably more neuro-muscularly mature and more perceptually and cognitively developed than younger infants and thus might demonstrate faster improvements in walking skill.

Spontaneous Activity—After infants begin walking, they generate immense amounts of practice, but how much they move varies widely among infants. During free play in a laboratory playroom, babies spend 25–75% of their time in motion and take 2000–6000 steps per hour (Hoch, O'Grady, & Adolph, 2019). Spontaneous locomotor activity is positively correlated with elapsed time walking and walking skill (Adolph et al., 2012; Cole, Robinson, & Adolph, 2016). However, correlations in previous work may be driven by the rapid improvements in walking skill in the first three to four months after walk onset when developmental trajectories are steepest. Relations among spontaneous locomotor activity, elapsed time walking, and walking skill are less clear after the initial spurt of improvement. Indeed, even infants with similar months walking show considerable variability in how much they move.

Further*, how* infants accumulate walking steps is also highly variable. When infants take their first independent steps, they can manage only a few slow steps in each bout. But after infants walk well enough for researchers to measure their gait patterns on both legs—at least 4 continuous forward steps at steady state velocity—they can take slow or fast steps at will, and they can produce short bouts of 1–3 steps or string together long sequences with dozens of steps (Lee, Cole, Golenia, & Adolph, 2018). And even after infants can walk quickly or produce long bouts consistently, the range of what infants choose to do varies widely. During free play in a laboratory playroom, infants' speed ranges from 20–140 cm/s, and short bouts of 1–3 steps account for 10–70% of their walking bouts (Lee et al., 2018). Spontaneous step rate reflects how quickly infants choose to move; the percentage of short bouts reflects how often infants stop and go; and both factors may reflect differences in walking skill—especially in the first few months of walking.

Body Factors—At every age, differences in body characteristics impose different biomechanical constraints on walking. Taller or heavier babies, for example, might walk or learn to walk differently. Indeed, overweight infants tend to begin walking at older ages than slimmer infants (Slining, Adair, Goldman, Borja, & Bentley, 2010).

Furthermore, experimental manipulations of infants' body dimensions directly affect walking skill. Infants display less mature walking patterns and incur more missteps and falls when wearing a diaper compared to walking naked (Cole, Lingeman, & Adolph, 2012), when wearing heavy pants compared to diapers (Theveniau, Boisgontier, Verieras, & Olivier, 2014), when loaded with small weights compared to unloaded (Garciaguirre, Adolph, & Shrout, 2007; Vereijken, Pedersen, & Storksen, 2009), and when carrying objects compared to hands free (Heiman, Cole, Lee, & Adolph, 2019; Mangalindan, Schmuckler, & Li, 2014). During free play, infants move less when loaded with 15% of their body weight compared to walking unweighted (Hoch, El Fadel, Selber, & Adolph, 2019). Yet, little is known about the effects of natural variations in infants' bodies on the development of walking skill.

Environmental Factors—The development of walking is also affected by the environmental context. For example, infants from homes with more available inside space display better gross motor skills (Saccani, Valentini, Pereirra, Muller, & Gabbard, 2013; Valadi & Gabbard, 2018). Less use of infant equipment like highchairs, car seats, and "exersaucers" predicts earlier walk onset ages (Abbott & Bartlett, 2001). In free play sessions in a laboratory playroom, infants move more when the environment offers toys designed for locomotion such as balls and toy strollers compared to toys designed for stationary play such as blocks and stuffed animals (Hoch, Hospodar, Alves, Selber, & Adolph, 2019). Moreover, infants playing in an empty room explore less of the room and stay closer to their caregivers compared to infants playing in the same room filled with toys (Hoch, O'Grady, et al., 2019).

Sociodemographic Factors—Sociodemographic factors such as race, ethnicity, and socioeconomic status affect infants' age at walk onset because they are associated with caregiving practices, which in turn enhance or limit opportunities for infants to practice upright movements (for reviews, see Adolph, Karasik, & Tamis-LeMonda, 2010; Adolph & Robinson, 2013, 2015). For example, infants from cultures that endorse rigorous handling and deliberate exercise begin walking several weeks to months earlier than cultures without formal handling and exercise routines (Hopkins & Westra, 1988; Super, 1976). Conversely, infants from cultures that limit opportunities for movement acquire their skills months later than infants who are free to move.

Sociodemographic factors can also influence the toys and social partners available for play, the space available in the home and neighborhood to move, and caregivers' provision of access to space. These factors may indirectly affect infants' bodies and environments and thereby opportunities available for movement (Valadi & Gabbard, 2018; Venetsanou & Kambas, 2010). However, researchers have not yet established whether sociodemographic factors affect the development of walking skill after infants have begun to walk.

Current Study

Although previous work shows that elapsed time since walk onset is the single best predictor of infant walking skill (e.g., Adolph et al., 2003), previous work also indicates that infants' motor behavior is constrained and facilitated by their bodies, home environments, and the childrearing practices of their families. Thus, body, environmental, and sociodemographic factors likely influence infants' moment-to-moment and day-to-day walking practice. These factors might shape the development of walking skill by influencing infants' walk onset age and/or the type or amount of locomotor activity infants produce. However, no study examined whether any of these factors—walk onset age, spontaneous activity, body dimensions, home environment, and sociodemographic factors—contribute to the development of walking skill.

We had the opportunity to examine the development of walking skill in two sociodemographically distinct groups of infants living in the same city. We recruited infants with a wide range in elapsed time walking from two hospitals that typically serve distinct communities. Our primary aim was to test whether naturally occurring differences in walk onset age, spontaneous locomotor activity, body dimensions, home environment, and sociodemographic factors predict infant walking skill, beyond the variance accounted for by time walking. Our second aim was to compare walking skill, walk onset age, locomotor activity, body dimensions, and home environments between samples to more fully characterize the potential role of sociodemographic factors on infant walking.

During a visit to our laboratory playroom, we measured infants' step length, step width, and speed with a pressure-sensitive gait mat. We selected these measures because they are fundamental indices of walking skill, easily understood by nonexperts, and redundant with more complex spatio-temporal measures such as percentage of cycle in double support, reciprocal arm swing, heel strike, and so on. We determined infants' crawl and walk onset ages from parent report, verified with laboratory observations. We recorded infants' spontaneous locomotor activity during 20 minutes of free play with their parents in our laboratory playroom and calculated the percentage of the session infants spent walking, step rate (steps per walking minute), and percentage of short bouts (1–3 steps). We measured infants' body dimensions and computed percentiles for height, weight, and weight-for-height, parents reported how much space was available inside their homes, and we used families' home addresses to estimate available outdoor space.

Method

Data Sharing

Videos of each infant's entire session, the demographic data, and video-coding spreadsheets are shared (with caregivers' permission) with authorized investigators in the Databrary library (https://nyu.databrary.org/volume/1273#panel-data). Exemplar video clips showing the procedures for measuring infants' walking skill on the gait mat and infants' spontaneous locomotion during free play, the video-coding manual, scripts for obtaining parent report of onset ages in English and Spanish, flat file processed data, and the analysis code are posted publicly in the Databrary volume.

Participants

We recruited two samples of infants in the greater New York City area: Bellevue (n = 38) and Langone (n = 44), named for the hospitals from which families were recruited. All infants were healthy and born at term. Families were reimbursed for travel expenses and received a photo magnet and tote bag as souvenirs of participation.

Prior to analyses, we quasi-randomly selected the current dataset from a larger dataset to balance the spread in infants' sex and age across samples as best as possible. In both samples, 13-, 15-, and 19-month-old infants (52% female) were tested within two weeks of their target age (Bellevue: *n*s = 11, 11, and 16 infants; Langone: *n*s =12, 17, and 15 infants, respectively), Figure 1A. Gait data from a subset of infants from both samples were reported previously in Lee et al. (2018) and Heiman et al. (2019), and infant-mother interactions from a subset of infants in the Langone sample were reported in Hoch et al. (in press); https://nyu.databrary.org/volume/89, https://nyu.databrary.org/volume/459 and https://nyu.databrary.org/volume/943, respectively. All infants could walk independently, but as expected, they differed widely in elapsed time walking and walking skill.

Sociodemographic Factors—Parents reported children's *ethnicity* as Hispanic/Latinx (56%), non-Hispanic/Latinx (42%), or chose not to report (2%), which we dichotomized as Hispanic or other. Parents reported children's *race* as Asian (1%), Black/African-American (2%), other (29%), White (38%), multiple races (10%), or chose not to report (20%), which we dichotomized as White or other. Parents reported their *language* to infants as primarily English (46%), equally English and another language (17%), or primarily a language other than English (37%), which we dichotomized as English or other. If parents indicated that Spanish was their primary language, the session was conducted in Spanish. One bilingual experimenter conducted sessions in Spanish and English to minimize any differences due to parent language. Parents reported the *education* level of both parents in terms of years of education, which we dichotomized as both parents held less than a 4-year college degree (48%) or at least one parent had a 4-year college degree or higher (52%). Analyzed with the dichotomous groupings, infants in Bellevue and Langone differed on all four measures, *t*s (80) > 6.26, *p*s < .001 (Figure 1B). Although the inclusion of two samples is beneficial for increasing the diversity of the participants overall, the sociodemographic factors we measured (ethnicity, race, caregiver language, and caregiver education) were confounded and did not hold unique statistical or conceptual value, reflecting the reality of intersectional identities; as such, we used sample membership as a proxy for global differences in sociodemographic factors.

Procedure and Playroom

Walking Skill—We measured infants' walking skill as they walked in a straight path over a pressure-sensitive gait mat (Gaitrite mat, 0.9 m wide × 5.7 m long, gaitrite.com; Protokinetics mat, 1.2 m wide × 4.9 m long, protokinetics.com; both 120 Hz, 4 sensors/in^2). The experimenter placed infants upright at one end of the mat and parents sat at the other end and encouraged infants to walk to them using enticing toys and snacks (Figure 2A and see https://nyu.databrary.org/volume/1273/slot/51294/-?asset=295601). Infants were barefoot and wore only a diaper and t-shirt during the study so that their legs and feet were visible, and movement was unimpeded. The parent and experimenter encouraged infants to walk as quickly as possible straight to their parent without stopping. If infants veered off the mat, stopped, or fell, we repeated the trial, aiming for at least six trials.

Spontaneous Activity—To assess spontaneous locomotor activity, we video-recorded 20 minutes of infants' free play in a large laboratory playroom (6.0 m × 9.4 m) with seven elevations: a couch, padded pedestal, small wooden box, raised platform, carpeted slide with carpeted stairs, stand-alone carpeted stairs, and wooden stairs (Figure 2B and see https://nyu.databrary.org/volume/1273/slot/51294/-?asset=295603). Six toys were placed in specified locations around the room: toy car, rattle ball, plush dog, jingling apple, musical saxophone, and crocodile xylophone. Parents were told to play with their infants as they normally would and to mind infants' safety.

We filmed infants from four synced camera views: a fixed overhead view, two fixed side camera views, and a hand-held video camera operated by a researcher to record a closer view of infants' leg movements. The researcher remained at the periphery of the playroom and did not interact with infants or parents.

Walk and Crawl Onset Ages—In a structured interview, parents reported infants' onset ages for walking and hands-knees crawling (https://nyu.databrary.org/volume/1273/slot/55662/-?asset=337453 for script in English, https://nyu.databrary.org/volume/1273/slot/55662/-?asset=337655 for script in Spanish). Onset dates were confirmed with calendars, baby books, home videos, or photos, if available (Adolph et al., 2003), and skills were verified in the laboratory session. As in previous work (Adolph et al., 2012; Cole et al., 2016; Hoch, O'Grady, et al., 2019; Lee et al., 2018), walk onset was defined as the first day caregivers saw their infants walk three meters across a room without stopping, falling, or holding onto anything for support. This criterion is more stringent than the standards published by the World Health Organization (WHO; Martorell et al., 2006), but it ensured that all infants could walk well enough to produce consecutive series of steps for analyses of walking skill. Walk onset age was missing for 2 infants, 1 in each sample. We calculated elapsed time walking as test age minus walk onset age (presented in months).

Caregivers also reported crawl onset based on the first day caregivers saw their infants crawl with their belly off the floor a distance of three meters without stopping or falling. Only 30 infants in the Bellevue sample and 37 in the Langone sample had useable crawl onset ages because 7 caregivers could not recall when their infant began crawling (4 from Bellevue and 3 from Langone) and 6 reported that their infant never hands-knees crawled to criterion (4 from Bellevue and 2 from Langone). We found no differences in walk onset ages between infants with and without crawl onset ages ($t(78) = -.29$, $p = .77$).

Body Factors.—We measured infants' recumbent *height* on a measuring board, and *weight* on a pediatric scale. Infants' *height percentile*, *weight percentile*, and *weight-for-height percentile* were calculated based on WHO standards (2011). Height was missing from 3 infants (1 from Bellevue and 2 from Langone) and weight was missing from 1 Bellevue infant because infants became fussy.

Environmental Factors—In a structured interview, parents reported the number of rooms in their homes and the number of adults and children who lived in their home. Kitchens, bathrooms, hallways, and walk-in closets were not counted as rooms (Solari & Mare, 2012). We divided the total number of people (adults and children combined) living in the home by the number of rooms to calculate the number of people per room as an index of *indoor space*. Parents also drew a map of the layout of their home or provided a floorplan to corroborate their reports. Six parents (2 from Bellevue and 4 from Langone) did not provide data on the number of rooms in their homes.

We also geocoded families' home addresses and used data from NYC Open Data (https://opendata.cityofnewyork.us/) to determine how many square miles of *outdoor space* were available within a 0.5-mile radius of the home (sf package, R). Outdoor space was missing for 5 Langone infants because the homes were not within the NYC Open Data boundaries (2 NJ addresses, 3 NY addresses).

Data Processing

Measures of Walking Skill—As is customary, we first eliminated one to three steps from the beginning and end of each walking sequence to discard steps when infants were speeding up and slowing down (Hoch, O'Grady, et al., 2019; Lee et al., 2018). We then eliminated segments of walking with less than four steps (the minimum for gait measures on both legs) and segments that were not forward, continuous, and straight. Of the remaining walking segments, we averaged the two fastest sequences for final analyses. As in previous work (Cole et al., 2016; Lee et al., 2018), we calculated three measures of walking skill: *step length* (front to back distance between consecutive steps), *step width* (side to side distance between steps), and *speed* (distance traveled from the first to last step divided by time); Figure 2C.

Video Coding of Spontaneous Activity—Coders scored infants' locomotor activity using Datavyu video-coding software (datavyu.org) that allows frame-accurate identification of user-defined events and time locks the onsets and offsets of the events to their location in the video. Coders identified each walking bout based on inter-bout intervals of at least 500 ms (Adolph et al., 2012; Cole et al., 2016; Hoch, O'Grady, et al., 2019; Lee et al., 2018); the 500 ms criterion was based on infants' typical double support period during standard gait (time between steps when both feet are on the ground), which is less than 500 ms (Bril & Breniere, 1989). Bout onset was the first video frame when the foot lifted off the ground, and bout offset was the first video frame when the foot returned to the ground. Then, coders counted the number of steps in the bout. Bouts could contain one or more steps (Adolph et al., 2012; Cole et al., 2016; Lee et al., 2018).

To determine the *percentage of session spent walking*, we calculated infants' accumulated bout durations and divided by the total task time. To determine *walking step rate* (how quickly infants moved), we divided the accumulated number of walking steps by accumulated time infants walked during free play. To determine the *percentage of short bouts* (bouts with only 1–3 steps), we divided the number of short bouts by the total number of walking bouts. We excluded data from three Langone infants who were identified as outliers because they spent less than 5% of the session walking.

A primary coder scored 100% of the video data and a second coder independently scored 25% of each infant's free play data to test inter-observer reliability. The second coder independently scored 25% of each infant's data rather than a subset of infants to ensure that differences among infants were captured. For steps per bout, bout duration, and total number of bouts, correlations between coders were high; rs ≥ .98, ps < .001. To avoid coder drift, after every few sessions, the coders met to review disagreements. Although the number of disagreements was small, to avoid propagating known errors (typos, careless errors) into the final dataset, such errors were corrected. For true disagreements (e.g., where the feet were obscured, one coder saw a "step" and the other saw a "pivot"), the primary coder's data were retained.

Statistical Analyses

Sample membership was coded as a binary variable (Bellevue = 1 and Langone = 0). We computed elapsed time walking as months walking for ease of interpretation. We first tested sample differences in walking skill, walk onset age, locomotor activity, body dimensions, and environmental factors using t-tests. We also conducted two sets of multiple linear regression models, one with walk onset age as the outcome variable and one with locomotor activity measures as the outcome variables, to determine which factors were most strongly associated with sample differences in walk onset age and locomotor activity. We then assessed whether onset ages, locomotor activity, and sociodemographic factors explain additional variance in walking skill beyond that explained by months walking. We conducted simple linear regression models with walking skill measures as outcome variables, and months walking as the sole predictor. We compared the fits of these simple models (one for each measure of walking skill) to saturated multiple linear regression models including all predictor variables (months walking, walk onset age, spontaneous activity, body dimensions, home environment, and sociodemographic factors). We used SEM software (Lavaan package, R) to conduct all regression models to adjust for correlations between predictor variables and to adjust for missing data using a piecewise approach (Rosseel, 2012). Adjusting for body dimensions (height and weight), walking skill did not differ between boys and girls (ps>.13), so sex was collapsed in subsequent analyses.

Results

No Sample Differences in Walking Skill

Overall, neither walking skill (ts(80)<1.33, ps < .19; Figure 3A) nor elapsed time walking ($t(78)=1.42$, $p=.16$) differed between samples. As expected (and as a "sanity check" of the reliability of our outcome measures), in both samples, infants with more months walking took longer and narrower steps and walked faster (Figure 3B). Thus, measures of walking skill corroborated caregivers' reports of onset ages. Moreover, each measure of walking skill improved at the same rate in both samples: Bellevue rs(35) = .67, −.54, and .68, for step length, step width, and speed, respectively; Langone rs(41) = .67, −.60, and .64, for step length, step width, and speed, respectively.

To confirm that the rate of improvement in walking skill did not differ by sample, we ran two regression analyses with step length and step width as outcome variables. Previous work and visual examination of the data indicated that improvements in walking skill over months walking are better represented by a power function than a linear model, with faster improvements in the first few months after walk onset than in later months (e.g., Adolph et al., 2003; Bril & Ledebt, 1998). To estimate the inflection point across both samples when improvements in walking skill began to slow, we used nonlinear regression models (Marsh & Cormier, 2001). As shown by the dotted lines in Figure 3B, for step length, the inflection point was at 3.9 months of walking (SE = 0.7; 95% CI: 2.6, 5.3), for step width at 2.5

months (SE = 0.4; 95% CI: 1.7, 3.3), and for speed at 3.6 months (SE = 0.6; 95% CI: 2.5, 4.8). To approximate the power function between months walking and walking skill in the regression models, we used a segmented regression line that allows different slopes before and after the inflection point. We entered sample membership, the segmented linear splines (with the inflection points previously identified through the nonlinear regression analyses), and a sample membership × spline interaction as predictors, adjusting for test age. We found no main effect or interaction for sample membership; the novice and experienced splines predicted step length and speed (ps < .01) and the experienced spline predicted step width (p = .016; see Supplementary Tables 1A–C).

As expected based on previous work (e.g., Lee et al., 2018), step length and speed were strongly correlated, $r(80) = .92$, $p < .001$; that is, walkers took longer steps when they walked faster. Also as expected, step length and step width were only moderately correlated, $r(80) = -.59$, $p < .001$. Given the multicollinear nature of step length and speed, we used only step length and step width in further analyses. (Replacing step length with speed produced the same pattern of results.)

Sample Differences in Walk Onset Age

As shown by the horizontal lines in Figure 4A, Bellevue infants (M = 13.6 months, SD = 1.8) walked at later ages than did Langone infants (M = 12.4 months, SD = 1.6; $t(78) = -3.14$, $p = .002$). Based on the WHO standards, 54% of Bellevue infants and 33% of Langone infants fell into the "late" 75th percentile for walk onset age (see region above blue shaded area in Figure 4A). Indeed, 35% of Bellevue infants but only 7% of Langone infants began walking beyond the 90th percentile (see region above top dashed blue line in Figure 4A).

Given differences in walk onset age, we also examined crawl onset age. Crawl and walk onset were positively correlated ($r = .51$, $p < .001$). Similar to walk onset, Bellevue infants (M = 9.5 months; SD = 1.8) began crawling approximately one month later than did Langone infants (M = 8.1 months; SD = 1.3; $t(67) = -3.64$, $p = .001$; Figure 4B); 58% of Bellevue infants and 21% of Langone infants had crawl onset ages beyond the 75th WHO percentile; 36% of Bellevue infants and 5% of Langone infants had crawl onset ages beyond the 90th percentile.

We conducted a multiple linear regression model to assess the relation between sample membership, crawl onset age, and walk onset age. We tested main effects and interaction effects for sample membership and crawl onset age on walk onset age, first adjusting for the relation between sample membership and crawl onset age. Sample membership predicted crawl onset age ($p < .001$), and crawl onset predicted walk onset ($p = .005$), but sample membership had no direct effect on walk onset age ($p = .79$), nor did the interaction term ($p = .89$), after adjusting for crawl onset age (Supplementary Table 2). In other words, Bellevue infants' crawl and walk onset dates were shifted by approximately one month later compared to Langone infants, but there was no evidence that the relation between crawl and walk onset differed between groups.

Sample Differences in Spontaneous Activity

As shown in Figure 5, during free play, Bellevue infants (M = 20%, SD = 6%) spent more of the session walking than did Langone infants (M = 16%, SD = 6%); $t(77) = -2.89$, p = .005. But Bellevue infants moved more slowly, as indicated by a lower step rate (Bellevue: M = 136 steps/min, SD = 18; Langone: M = 145 steps/min, SD = 17); $t(77) = 2.07$, p = .04. Infants in both samples (Bellevue: M = 40%, SD = 12%; Langone: M = 38%, SD = 10%) initiated the same percentage of short bouts, $t(77) = -0.69$, p = .49.

To test which factors related to these differences in locomotor activity, we conducted multiple linear regression models using sample membership, walk onset age, and months walking to predict each measure of locomotor activity. We first adjusted for the relation between sample membership, crawl onset, and walk onset (by adding two initial paths, one with sample membership predicting crawl onset age and a second with crawl onset age predicting walk onset age per the results of the previous models; see Supplementary Table 2) but did not include crawl onset as a direct predictor of locomotor activity. After adjustments, sample membership predicted the percentage of the session spent walking (p = .007) and step rate (p = .033; Supplementary Table 3). Bellevue infants spent 4% more time walking compared to Langone infants, and took 9 fewer steps per minute. Months walking also predicted infants' step rate, but each month walking was only associated with an increase of 2 steps per minute (p = .024). In sum, slight differences in locomotor activity may exist between samples, but no singular factor robustly predicted measures of locomotor activity: Sample membership predicted differences in the percentage of the session spent walking and step rate, and months walking further predicted differences in step rate.

Sample Differences in Environmental but not Body Factors

Infants' height, weight, and weight-for-height spanned the 1st to 99th percentiles (based on WHO standards), but samples did not differ on any measure of body dimensions (Figure 6A; ts < .82, ps > .42). As shown in Figure 6B, the homes of Bellevue infants (M = 2.07, SD = 0.81) had approximately one more person per room than the homes of Langone infants (M = 1.13, SD = 0.42), suggesting less indoor space to move, $t(74) = -6.47$, p < .001. Bellevue infants (M = 0.04, SD = 0.05) also had slightly fewer square miles of parks within a 0.5 mile radius of their home than did Langone infants (M = 0.07, SD = 0.07), but the difference in outdoor space was not significant, $t(75) = 1.65$, p = .10.

Walking Skill Predicted by Months Walking, Indoor Space, and Spontaneous Activity

Walking skill, body factors, and outdoor space did not differ between samples, but Bellevue infants walked later than did Langone infants, exhibited small differences in activity, and had less indoor space. To simultaneously test the effects of all factors on walking skill, we conducted multiple linear regression models for step length and step width, with months walking, walk onset age, locomotor activity (percentage of session spent walking, step rate, percentage of short bouts), body factors (height percentile, weight percentile, and weight-for-height percentile), environmental factors (indoor and outdoor space) and sample membership as predictors.

As in the previous models, we first adjusted for the relation between sample membership, crawl onset, and walk onset (by adding two initial paths, one with sample membership predicting crawl onset age and a second with crawl onset age predicting walk onset age per the results of the previous models; see Supplementary Table 2) but did not include crawl onset as a direct predictor of walking skill. We also adjusted for the relation between sample membership and indoor space by adding a third path with sample membership predicting indoor space. To represent the nonlinear relation between months walking and skill in our path model, we entered a segmented linear spline, with an inflection point at 3.9 months for step length and 2.5 months for step width, per the results of the nonlinear regression analyses. Finally, we adjusted for the correlation between both pairs of splines, and between step length and step width.

The model explained 57% of the variance in step length and 56% of the variance in step width. A reduced model, with only the linear splines predicting step length and step width, explained 46% of the variance in step length and 33% of the variance in step width.

Months walking strongly predicted walking skill, and the rate of improvement was steeper before the inflection point than after the inflection point, even after adjusting for all other factors (Figure 7). With each month of walking, "novice walkers" increased step length by 2.2 cm, and decreased step width by 1.8 cm. In contrast, with each month of walking, "experienced walkers" increased step length by only 1.6 cm, and decreased step width by only 1.0 cm. Furthermore, adjusting for all other factors, more crowded homes predicted shorter steps and larger step widths. Each additional person per room decreased walking skill at the magnitude of approximately one month of walking—with each additional person per room, step length decreased by 1.5 cm, and step width increased by 0.9 cm. Although the distribution of people per room differed by sample, with Bellevue families reporting more crowded homes, the relation between home crowding and walking skill emerged after adjustments, including adjustments for sample membership. This means that home crowding explains unique variance in walking skill, beyond differences between samples. Moreover, spontaneous locomotor activity predicted walking skill. A higher percentage of short walking bouts predicted shorter steps, and a smaller percentage of the session spent walking predicted wider steps; a 10% decrease in the percent of short walking bouts was related to a 1.1 cm increase in step length, and a 10% increase in the percent of the session spent walking was related to a 1.2 cm decrease in step width.

Sample membership, body factors, and step rate were not related to step length or step width after adjustments (see Supplementary Table 4 for full model). To summarize, months walking was the most salient predictor of walking skill, with rapid improvements in the first 3.9 months for step length and 2.5 months for step width, and slower improvements past those inflection points. But walking skill was also associated—to almost the same extent as one month of walking—with environmental factors (home crowding) and spontaneous locomotor activity (percentage of session spent walking and percentage of short bouts).

Discussion

What factors facilitate the development of walking skill? The current study suggests several answers. First, although elapsed time since walk onset is a powerful predictor of infant walking skill (for reviews, see Adolph & Robinson, 2013, 2015), previous work largely ignored other potential influences on development. Here, we found that months walking retained its predictive power even after statistically adjusting for all other factors —infants' age at walk onset, their spontaneous locomotor activity, and variations in their body dimensions, environments, and sociodemographic backgrounds—indicating that elapsed time since walk onset captures something important, albeit unspecified, about the development of walking skill.

Second, even after adjusting for months walking and other factors, aspects of infants' environments (indoor space) and spontaneous behaviors (percentage of session spent walking and percentage of short bouts) explained unique variance in walking skill. To our knowledge, this is the first study to find any factor aside from months walking that strongly predicts walking skill, meaning that months walking does not "swamp" the predictive power of all other factors. Indeed, aspects of infants' environments and spontaneous activity predicted sizable differences in walking skill: Each predictor unit (one person per room, 10% change in activity) was nearly equivalent to the effect of one month of walking.

Third, despite robust group differences in sociodemographic factors and age at walk (and crawl) onset, neither sample membership nor walk onset age played a significant role in the development of walking skill, suggesting that infants in both groups were on a level playing field after they began walking. And finally, despite previous findings that experimental manipulation of infants' body dimensions affects walking skill (e.g., Garciaguirre et al., 2007; Hoch, El Fadel, et al., 2019), and despite a wide range in infants' natural body dimensions (spanning the 1^{st} to 99^{th} percentiles) in the current study, individual differences in natural growth had no reliable impact on walking skill (see also Adolph et al., 2003).

Walk Onset and Months Walking

To accrue walking practice, infants must begin walking, but definitions of skill onset are arbitrary and largely dictated by convenience. Moreover, the definition affects the values of the measures or whether the skill can be measured at all. Here, we defined walk onset as the first day infants walked three meters across a room without stopping or falling to ensure that all infants walked well enough to produce a consecutive series of steps for obtaining standard gait measures during steady state velocity. But there is no definitive and absolute Platonic definition of walk onset or any other skill. Before infants can walk three meters, they can take independent steps in smaller bursts, and before that they can take single steps, and before that they can walk with support, and so on (Adolph, Robinson, Young, & Gill-Alvarez, 2008). An earlier starting point, such as the first day infants can take five independent steps as on the WHO standards, would change the measured values and indeed would reflect different measures (including gait initiation and termination rather than steady state walking).

Regardless of the chosen starting point, age at onset likely reflects the overall readiness of the system to perform the task defined by the criteria for onset. To walk three meters, as we defined walk onset, infants must first develop sufficient postural control, coordination, and leg strength. Notably, our results suggest that for walking skill, after the system is "ready," improvements in walking skill are the same, regardless of age at onset. In contrast to skills with a critical or sensitive period like vision and language, age at walk onset does not appear to affect the development of walking skill, at least for infants who begin walking in the normative range.

Walk onset starts the clock for months walking. However, the clock does not reflect the same thing with each passing day. Indeed, most infants pass the criterion for walk onset on one day, but not on the next—regardless of whether the criterion is one step, 5 steps, or 10 steps. Rather, motor skills stutter into infants' repertoires with a variable "on-off" trajectory, rather than abruptly as in a step function (Adolph & Robinson, 2011; Adolph et al., 2008). And variable trajectories can last for several weeks after the first day infants pass criteria.

Perhaps most critical, measures of elapsed time since onset carry no explanatory power. Although months walking is a robust predictor of walking skill, both in previous work and in the current study, it is only a crude approximation of infants' actual accumulated practice coping with a variable body in a variable world. Put another way, without knowing the actual content of infants' everyday walking experience, months walking is a powerful predictor with no explanatory power (Adolph & Berger, 2006; Adolph & Robinson, 2013, 2015). The remedy is a detailed, longitudinal description of the quantity, quality, and distribution of infants' everyday practice with walking—how much infants move, the size of each walking bout, how bouts are distributed, the ground surfaces infants step on, how often they experience each surface, and so on—and such a description would be a tremendous undertaking.

So, what aspects of practice might months walking reflect? Likely, months walking captures differences among infants in approximate walking practice across a time span that includes both novice and experienced walkers or a time span that includes the first few months after walk onset when improvements are most rapid. The wide range in months walking in this study (Figure 3) strengthened the correlation between months walking and walking skill. But within narrower time bands, months walking loses its predictive power (e.g., see the wide range in skill at two months of walking for step length, step width, and speed in Figure 3). Thus, months walking correlates with walking skill for samples that span a wide time range, such as infants with one and five months of walking (step length: $r(26) = .68$, $p < .001$, step width: $r(26) = -.58$, $p = .001$) or for samples of novice walkers when improvements are most rapid, such as infants with one and two months of walking (step length: $r(34) = .45$, $p = .006$, step width: $r(34) = -.50$, $p = .002$). But the correlation dissipates when improvements are less steep, such as for infants with five and six months walking (step length: $r(15) = -.12$, $p = .66$, step width: $r(15) = -.35$, $p = .17$).

Spontaneous Activity as an Indicator of Practice

Practice regimens, including the total quantity, distribution, and type of practice, matter for skill development. Indeed, we found that a greater percentage of the session spent walking predicts narrower step widths and a smaller percentage of short bouts predicts larger step lengths. Of course, we cannot know for certain whether infants' spontaneous activity in our laboratory playroom holds in other contexts. In principle, the novelty of the laboratory environment could alter infants' activity, or their activity might be too inconsistent in any context to support extrapolation. However, it is unlikely that spontaneous locomotor activity in the playroom would predict walking skill if it did not reflect practice in daily life.

Assuming that differences in spontaneous locomotor activity reflect daily practice, then infants who walk more would accrue practice faster, thereby leading to greater skill. That is, extrapolated to larger time scales, small differences in infants' average daily activity add up. Of course, the relations between activity and skill could be in either direction given our cross-sectional design. Our interpretation assumes that infants who walk more develop better walking skill, but the opposite—that infants with better walking skill walk more—could also be true.

Moreover, practice regimens likely ramp up with development (Adolph et al., 2008). Just as reading the same children's book over and over would not lead to flexible reading skill, walking back and forth in straight lines would not lead to adaptive, flexible walking skill. In strength training, athletes must progressively overload their musculoskeletal system by increasing the amount of weight, number of repetitions, or total training time to increase muscle size, strength, and endurance (Kraemer, Ratamess, & French, 2002). Of course, parents do not coach infants in formal exercise programs. But how infants choose to move might reflect self-selected increases in challenge. For example, we found that a smaller percentage of short bouts predicted longer steps. Although short bouts persist across development (Lee et al., 2018), the predictive relation suggests that infants who challenge themselves to string together longer sequences of steps develop better walking skill. Indeed, training regimens for simulated robots shows that varied practice supports flexible, functional performance. Simulated robots trained on varied, infant-like paths perform better than those trained on repetitive, geometric paths, and robots trained on more varied infant paths outperform those trained on less varied paths (Ossmy et al., 2018).

Opportunities to Practice: Sociodemographic and Environmental Factors

We found a robust effect of sample membership on walking (and crawling) onset age, suggesting that sociodemographic factors affect the emergence of skills. Of note, the two samples used in this study are not representative of all sociodemographic factors, and it would be informative to study other samples, with different ranges of sociodemographic factors, in the future. In the current study, sample differences in onset ages might reflect differences in caregiver constraints on pre-walking infant behaviors. For example, in a study of infant activity (recruited from the same Bellevue population as in the current study), only 50% of mothers gave their infants daily "tummy time", only 34% placed their pre-walking infants on the floor, and 57% reported more than one hour per day of constrained time (Gross et al., 2017). Furthermore, 45% reported concern about allowing their infants unrestrained floor access because of possible injuries due to the presence of other children, pets, or vermin. More generally, infants who spend more time in the prone position (e.g., tummy time) begin crawling and walking earlier than infants with less time in prone (Davis, Moon, Sachs, & Ottolini, 1998; Dudek-Shriber & Zelazy, 2007), which could explain the later onset ages of Bellevue infants, if the caregivers in our study followed similar practices.

Environmental Effects on Walking Skill—The US Census classifies homes as "crowded" if they contain more than one person per room (Blake, Kellerson, & Simic, 2007). By this definition, all of the homes of Bellevue infants and about half of the homes of Langone infants would be classified as crowded. Despite differences in average indoor space by sample, indoor space—not sample membership—predicted walking skill. For a skill like walking, crowding changes infants' opportunities to practice walking. Indeed, previous research found lower levels of gross motor skills in infants from more crowded homes (Widmayer et al., 1990). Outdoor space may not have predicted walking skill because infants spend more time inside the home, and use of outdoor space depends on many factors such as weather, presence of child-friendly areas, and neighborhood safety, which we did not assess.

Conclusions

A century of work by developmental psychologists, movement scientists, and clinicians supports one particularly robust finding about walking skill: Months walking predicts improvements in walking skill, especially in the first several months after walk onset (Adolph & Berger, 2006; Adolph & Robinson, 2013, 2015; Ivanenko et al., 2007; Lacquaniti, Ivanenko, & Zago, 2012). But development, including the development of walking, does not happen in a vacuum. Rather, infants' opportunities to practice walking differ due to differences in home environments, spontaneous behavior, and caregivers' childrearing practices. We suggest that in characterizing the development of any skill, researchers must consider the definitions used to decide when a behavior emerges in development; the quantity, distribution, and type of practice; and broader factors such as individual and environmental constraints that shape behavior—and development—more generally.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Data Availability Statement

With caregivers' permission, videos of each infant's play session, demographic data, and coding spreadsheets are shared with authorized investigators in the Databrary digital library (https://nyu.databrary.org/volume/1273#panel-data). Exemplar video clips showing the procedures for measuring infants' walking skill on the gait carpet and infants during free play, the video coding manual, scripts to elicit parent report of onset ages, flat file processed data, and the analysis code are also posted publicly in the Databrary volume.

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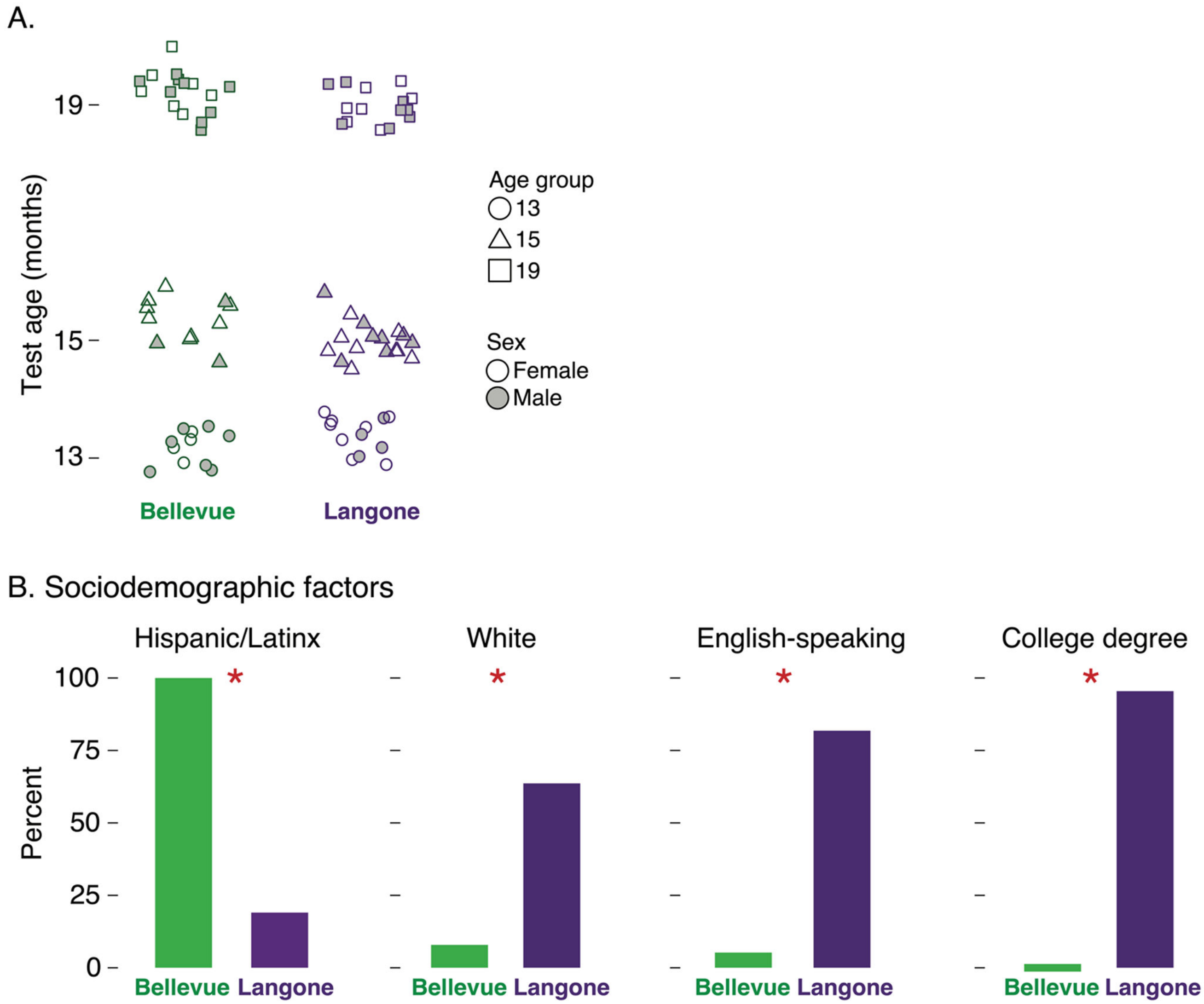

Figure 1.

Test age (A) and sociodemographic factors (B) for Bellevue (green) and Langone (purple) samples. Parent report measures for sociodemographic factors are shown dichotomized to illustrate sample differences. Asterisks denote significant group differences (*$p < .05$). Calculation of percentages for ethnicity and race include parents in the denominators who chose not to report ethnicity (Langone $n = 2$) or race (Bellevue $n = 14$, Langone $n = 2$).

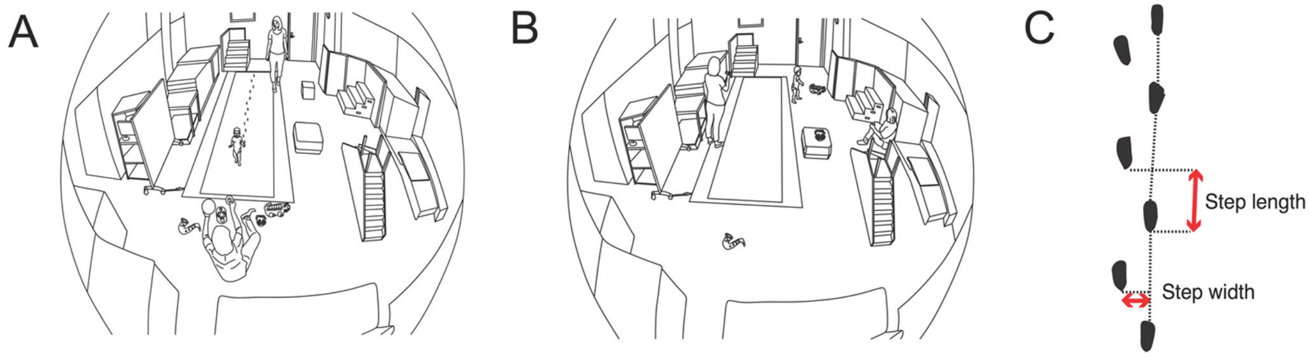

Figure 2.
Playroom set-up and calculation of walking skill. (A) Set-up for measuring infant walking skill: Experimenter (standing) carried infants to far end of pressure-sensitive mat (large rectangle), and caregivers sat at the other end of the mat and encouraged infants to walk straight toward them. (B) Set-up for measuring locomotor activity: Experimenter (standing) video-recorded infants and caregivers (shown seated) playing for 20-minutes in laboratory playroom. (C) Footfall measures of walking skill derived from gait mat. Step length is the front-to-back distance between steps; step width is the side-to-side distance between steps; and speed (not shown) is the distance traveled from the first to last step in a continuous sequence divided by travel time.

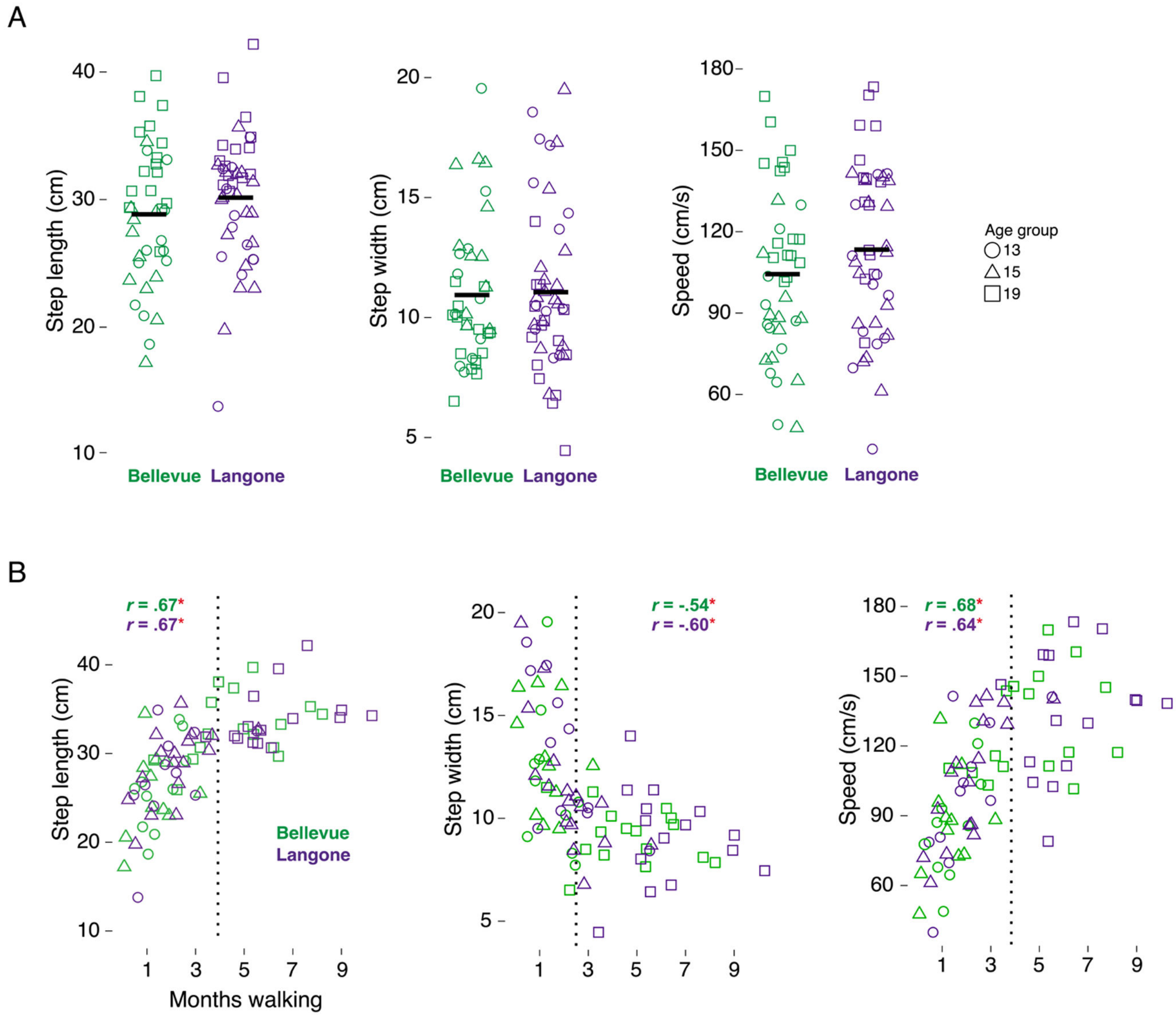

Figure 3.

Walking skill for Bellevue (green) and Langone (purple) samples. Each symbol represents averaged data for one infant. (A) Step length, step width, and speed for each sample. Horizontal bars denote group averages. (B) Step length, step width, and speed for each sample as a function of months walking. Correlation coefficients reflect rates of improvement for each sample. Clustering of circle and triangle symbols at early months and squares at later months reflects expected differences in months walking by infant test age. Vertical dotted lines denote the inflection point between faster rates of improvement in earlier months of walking and slower rates at later months estimated by nonlinear regression analyses: 3.9 months for step length, 2.5 months for step width, and 3.6 months for speed.

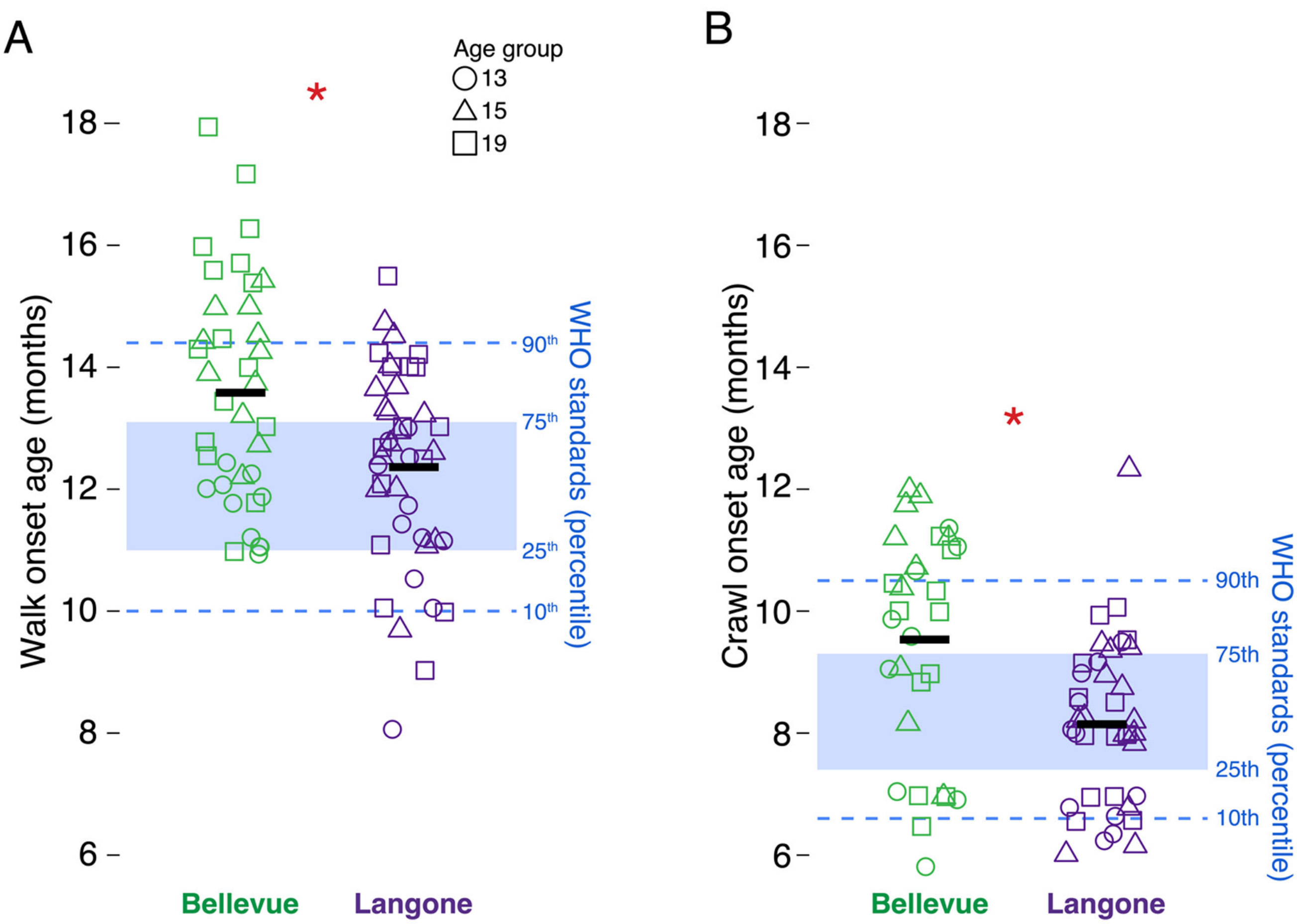

Figure 4.

Onset ages for Bellevue (green) and Langone (purple) samples. (A) Walk onset age. (B) Crawl onset age. Each symbol represents data from one infant. Horizontal black bars denote group averages. Asterisks denote significant group differences (*$p < .05$). Based on standards published by the World Health Organization (WHO), blue bands denote the 25th to 75th percentiles for walk and crawl onset ages; dashed blue lines denote the 10th and 90th percentiles. Across samples, walk onset age ranged from 8 to 18 months and crawl onset age ranged from 6 to 12 months. The distributions for onset ages in Langone infants straddles the 25th-75th percentiles, with approximately equal numbers of infants outside the 10th and 90th percentiles for walking and disproportionately more infants with early onset ages for crawling. In contrast, the distributions for onset ages in Bellevue infants are primarily beyond the 75th percentile, with disproportionately more infants beyond the 90th percentile for both walking and crawling.

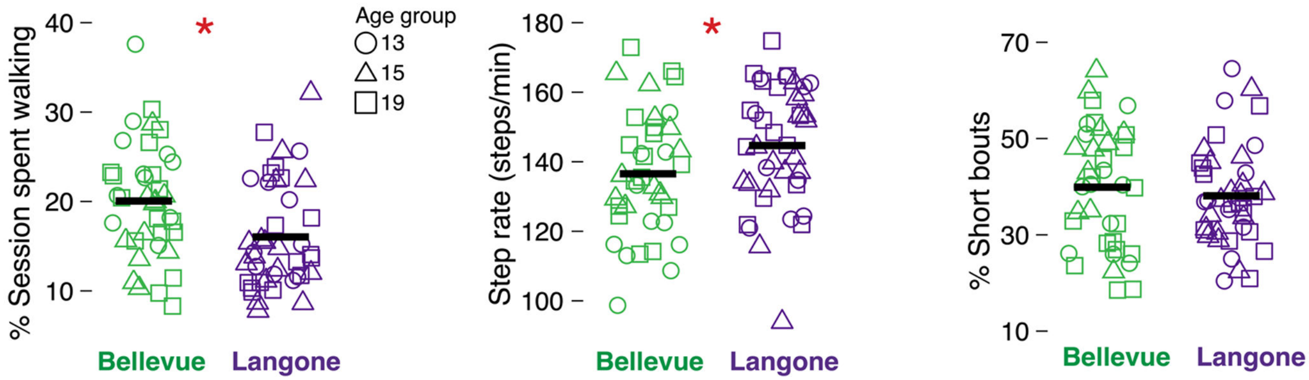

Figure 5.

Spontaneous locomotor activity during free play for Bellevue (green) and Langone (purple) samples for percentage of session spent walking, step rate (total number of steps divided by total time in motion), and percentage of short bouts (number of bouts with 1–3 steps divided by the total number of bouts). Each symbol represents data from one infant. Horizontal bars denote group averages. Asterisks denote significant group differences (*$p < .05$). Across samples, time in motion ranged from 8–40% of the session, step rate ranged from 90 to 170 steps/minute, and the percentage of short (1–3 step) bouts ranged from 20 to 70%.

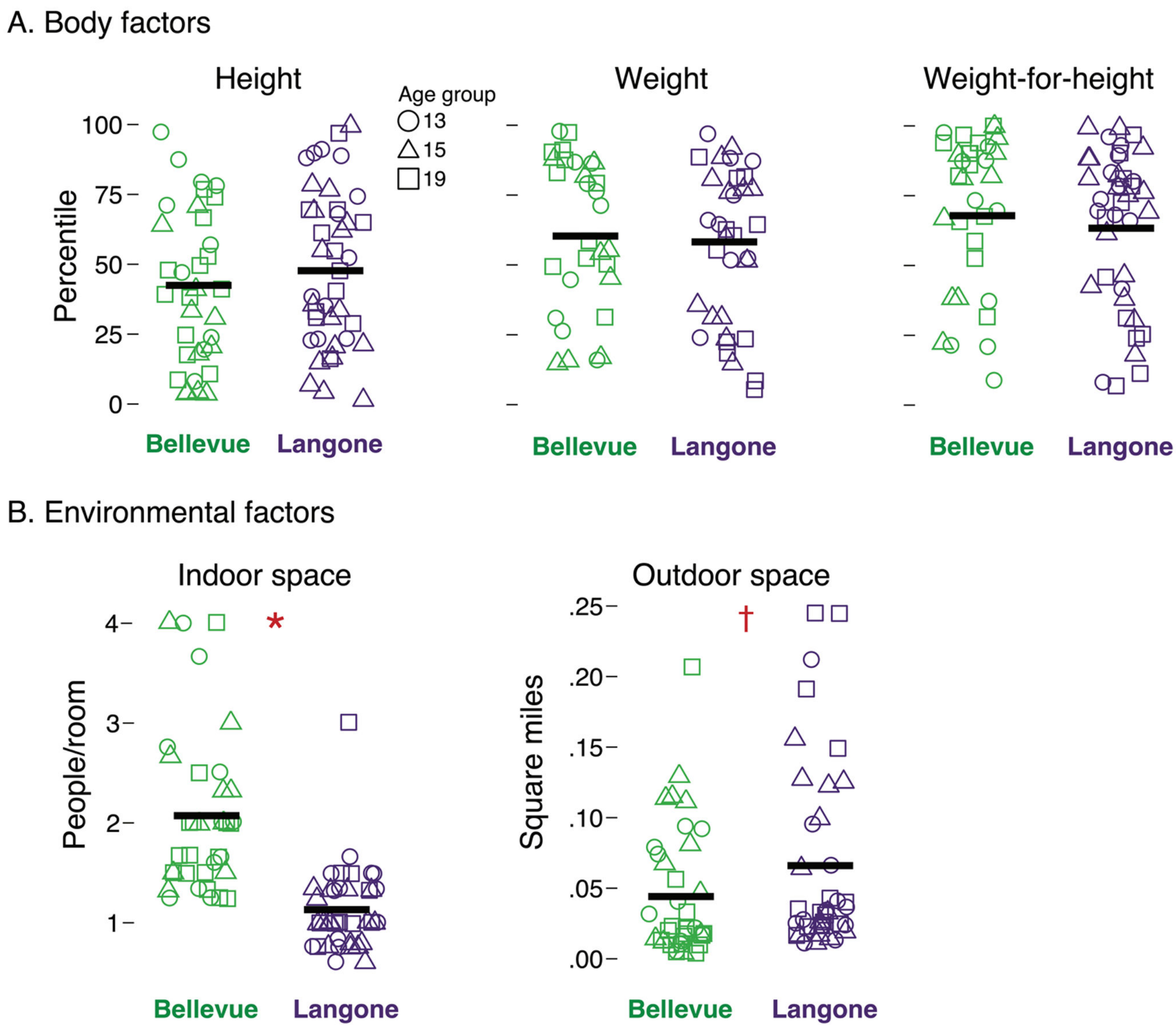

Figure 6.

Comparisons between Bellevue (green) and Langone (purple) samples for (A) body dimensions and (B) environmental space. Each symbol represents data from one infant. Horizontal bars denote group averages. Asterisks denote significant group differences (**p* <.05, $^{\dagger}p < .10$). Across samples, body factors spanned the 1st to 99th percentiles, people per room ranged from 0.5 to 4, and outdoor space ranged from 0.02 to 0.25 square miles.

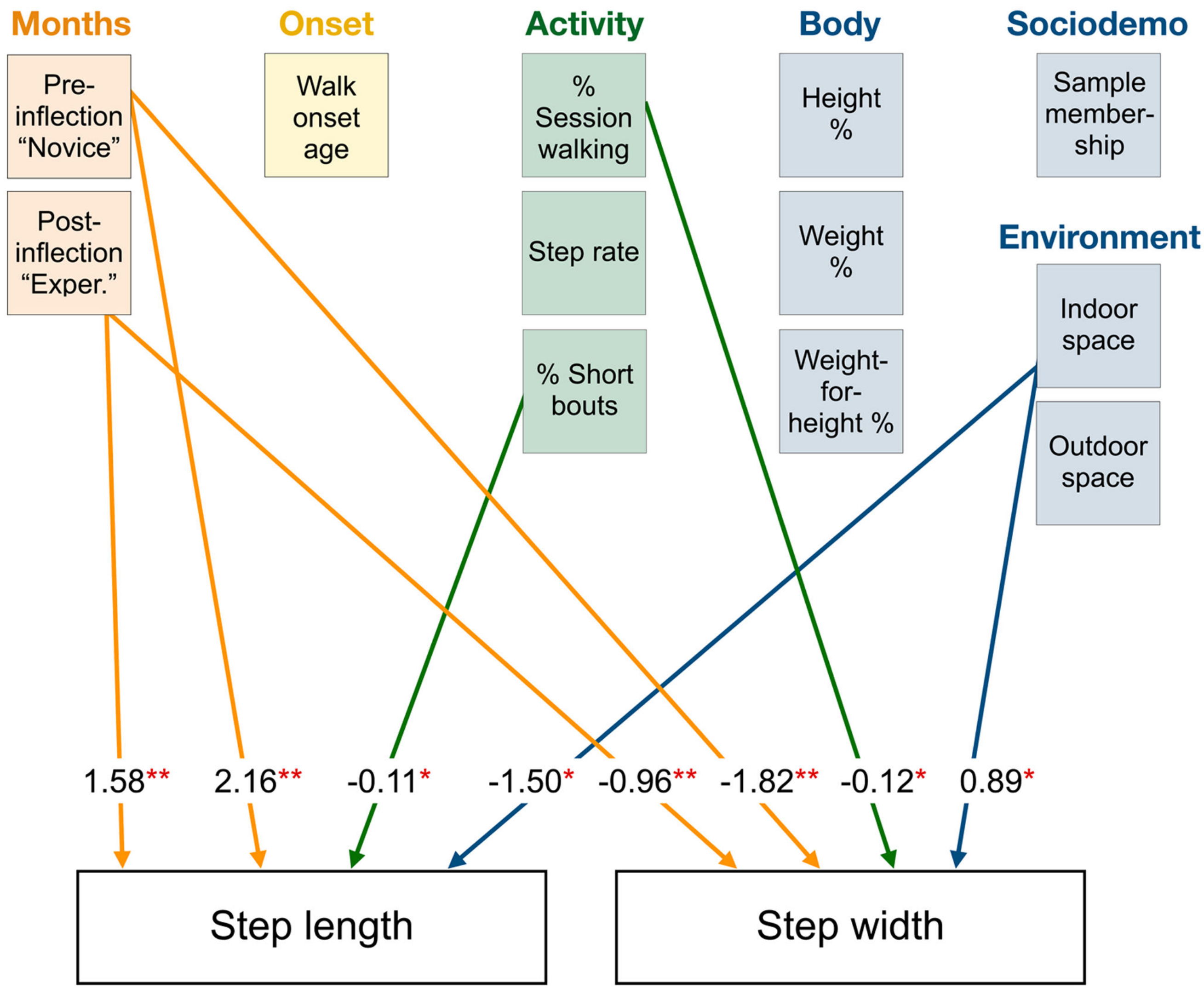

Figure 7.

Regression model for walking skill. Variables in each box along the top and right side of figure were entered as predictors for both outcome measures (step length and step width). Box and line colors reflect sets of conceptually related predictors. The measure "months walking" was split into two predictors based on the identified inflection points (less than and more than 3.9 months for step length, less than and more than 2.5 months for step width). Data for each measure of months walking were entered as separate variables to estimate effects of months walking before and after the inflection points. Significant predictors are denoted with arrows to outcome measures. Significant beta coefficients are denoted above each outcome measure (**$p < .01$, *$p < .05$). Larger beta coefficients reflect stronger predictive power, while statistically adjusting for other measures. Beta coefficients should be interpreted as the change in cm of step length or step width for each "1-unit" change in the predictor (e.g., an additional month of walking pre-inflection is associated with a 2.16-cm increase in step length; an additional person per room is associated with a 0.89-cm decrease in step width).