Published in final edited form as:

Dev Sci. 2021 September ; 24(5): e13069. doi:10.1111/desc.13069.

The Impact of Errors in Infant Development: Falling Like a Baby

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Abstract

What is the role of errors in infants' acquisition of basic skills such as walking, skills that require immense amounts of practice to become flexible and generative? Do infants change their behaviors based on negative feedback from errors, as suggested by "reinforcement learning" in artificial intelligence, or do errors go largely unmarked so that learning relies on positive feedback? We used falling as a model system to examine the impact of errors in infant development. We examined fall severity based on parent reports of prior falls and videos of 563 falls incurred by 138 13- to 19-month-old infants during free play in a laboratory playroom. Parent reports of notable falls were limited to 33% of infants and medical attention was limited to 2% of infants. Video-recorded falls were typically low-impact events. After falling during free play in the laboratory, infants rarely fussed (4% of falls), caregivers rarely showed concern (8% of falls), and infants were back at play within seconds. Impact forces were mitigated by infants' effective reactive behaviors, quick arrest of the fall before torso or head impact, and small body size. Moreover, falling did not alter infants' subsequent behavior. Infants were not deterred from locomotion or from interacting with the objects and elevations implicated in their falls. We propose that a system that discounts the impact of errors in early stages of development encourages infants to practice basic skills such as walking to the point of mastery.

Keywords

errors; falling; negative feedback; reinforcement learning; walking

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What if you wanted to design a system that could withstand immense amounts of use—much of it potentially harmful—like a well-traveled suitcase that is repeatedly bumped, thrown, and rolled over rough ground? And what if that system were a developing biological system that requires massive amounts of practice and self-generated activity, much of it fraught with errors? Perhaps a baby acquiring new motor skills, such as learning to walk? One potential solution is to value negative feedback from errors and even heavily weigh errors to facilitate learning. On this account, infants learn from their frequent mistakes—their walking missteps and falls. However, negative feedback from errors might dissuade

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All raw data and processed data are shared. With parents' permission, infants' video data and coding spreadsheets are openly shared with authorized investigators on Databrary.org at http://databrary.org/volume/1042. The coding manual, coding scripts (Databrary.org/volume/1042/slot/44651) and exported data and analysis scripts (Databrary.org/volume/1042/slot/44646) are publicly available. In addition, video clips of the procedure (Databrary.org/volume/1042/slot/44743) and exemplar infant falls (Databrary.org/volume/1042/slot/46744, databrary.org/volume/1042/slot/45029, and databrary.org/volume/1042/slot/44739) are publicly available.

infants from trying, and try they must to master basic skills. An alternative solution is to discount errors, so that falls go largely unmarked and infants primarily learn from positive feedback (Hoch et al., 2019). In this second scenario, infants can retain high motivation to practice their emerging skills, and learning relies primarily on positive feedback when infants accomplish their goals. The optimal solution, of course, depends on the cost and impact of errors. Similarly, a formal model of "reinforcement learning" used in robotics and artificial intelligence would need to decide whether (and how much) to weigh negative feedback relative to the positive rewards of successful performance (Kaelbling, Littman, & Moore, 1996).

Infant falls—errors in balance and motor control—provide a promising model system for understanding the impact of errors in early development. Falls are common, everyday events. Moreover, because falls involve a disruption in ongoing activity and the body impacts the ground, falling errors are tangible to infants and easily observable by researchers.

"Impact" has a technical meaning in terms of forces. Fall impact results from inadvertent, forcible contact with the ground, and the size of the impact depends on the height of the fall, mass of the body, and speed of the prior movement. "Impact" also has a broader meaning in terms of significance. Perhaps Haldane (1927) said it best: "To the mouse and any smaller animal, [falling] presents practically no dangers. You can drop a mouse down a thousand-yard mine shaft; and, on arriving at the bottom, it gets a slight shock and walks away…A rat is killed, a man is broken, a horse splashes" (p. 19). To the mouse, the physical impact is minimal, and falls are not especially salient. Not so for the man or the horse.

The extant literature, however, presents a conundrum: On the one hand, falls are a leading cause of accidental injury and death in infants and toddlers (Borse et al., 2008; Peden et al., 2008). On the other hand, infant falls are so frequent as to be commonplace, but rarely result in injuries (Adolph et al., 2012). How then shall we understand the cost and impact of infant falls?

High-impact, High-cost Falls

Infant falls can reflect high-impact, high-cost errors involving head and brain injuries, fractures, and deep cuts (Borse et al., 2008; Hyder et al., 2009; Peden et al., 2008). But serious injuries (and death) are limited primarily to falls from a sizeable height such as a balcony, window, or playground equipment (American Academy of Pediatrics, 2001; Lallier, Bouchard, St-Vil, Dupont, & Tucci, 1999). Unfortunately, at early stages of walking, infants lack the perceptual-motor knowledge to avoid falling from heights. In laboratory experiments, novice walkers walk over the brink of impossibly high drop-offs, steep slopes, and narrow bridges, requiring rescue by an experimenter to ensure their safety (for reviews, see Adolph & Hoch, 2019; Adolph & Robinson, 2015).

Fortunately, despite the danger of falling from high elevations outside the laboratory, falls that incur serious injury are rare. Only a tiny proportion (3%) of infants contribute to the dire statistics for falls (Borse et al., 2008). The World Health Organization conceptualized fall severity as a multi-tier injury pyramid, where the smallest top tier represents falls that result in death, and each successively larger, lower tier represents falls that cause permanent disability, long- and short-term hospitalization, and medical treatment, respectively (Peden et al., 2008).

Falls can also reflect high-impact, high-cost errors in elderly people (see Robinovitch's poignant video examples of real-life elderly falls at Databrary.org/volume/739), but with instructive differences compared to infants. Like infants, falls in elders are a leading cause of accidental injury, hospitalization, and death (Centers for Disease Control and Prevention, 2005). However, in contrast to infants, elderly people do not need to fall from a height to sustain injury; same-level falls are frequently injurious (Sterling, O'Connor, & Bonadies, 2001). Although elderly falls are measured in yearly rather than hourly rates (Robinovitch et al., 2013), a third of the people who fall sustain injuries that require medical treatment and thus twice as many elderly people (6%) contribute to their dire statistics compared with infants (Centers for Disease Control and Prevention, 2005; Stevens, Mack, Paulozzi, & Ballesteros, 2008).

Why are elderly falls so dangerous, even on flat ground? Elderly fall injuries reflect a series of failures, starting with the initial loss of balance and ending with the final impact (Cummings & Nevitt, 1989). Due to slow reaction time, reduced muscle strength, and impaired cognitive abilities, elders lack effective reactive behaviors to mitigate impact forces —behaviors that occur after losing balance prior to impact of sensitive body parts (hips, torso, and head)—taking reactive steps to regain balance, grabbing nearby supports to reduce speed of falling, and extending arms to arrest the fall. When elders fall onto sensitive body parts, soft tissues (skin, fat, muscle) fail to absorb the impact energy generated by the fall. Fractures occur because the residual energy exceeds the strength of elderly bones. Perhaps due to the high cost of falls, elderly people develop fear of falling and alter their walking patterns (Chamberlin, Fulwider, Sanders, & Medeiros, 2005; Vellas, Wayne, Romero, Baumgartner, & Garry, 1997).

Low-impact, Low-cost Hypothesis

For infants learning to walk, high-impact falls are unlikely to play an important role—such falls are too rare. Moreover, falls that do not require medical intervention are entirely missing from epidemiological reports, and no research examined infant fall severity by direct observation. Researchers do know, however, that new infant walkers fall every few steps. Over the next 10 months of walking, falling remains frequent. The average toddler falls 17 times/hour during everyday activity (Adolph et al., 2012; Adolph & Hoch, 2019). How significant then are infant's frequent, everyday falls that are missing from medical reports?

In contrast to high-cost errors at later periods of development, we hypothesize that the physical and social system has a high tolerance for errors early in development. Medical records indicate that short-distance falls are unlikely to cause significant injuries in infants and young children (e.g., Lyons & Oates, 1993). Safety gates block household stairs, bars block infant-accessible windows (e.g., Spiegel & Lindaman, 1977), and infants are protected by vigilant caregivers. Moreover, biomechanical factors determine the amount of potential energy generated by falling (Hayes et al., 1993). Infants' reactive behaviors and small bodies could mitigate potentially injurious impact forces and render falling low cost. However, no research examined infant's reactive behaviors when losing balance or the biomechanical consequences of their small stature and slow movement speed. We sought to reveal the prevalence and test the importance of lower tiers in the pyramid of fall severity—a "pyramid of pain" that extends beyond that based solely on medical reports. As shown in Figure 1A, we hypothesize much broader lower tiers that do not cause death or require medical treatment (tiers 1–2) but are remembered by caregivers months after the fall (tier 3), salient in the moment (tier 4), or go completely unmarked (tier 5).

If we are correct that falling is largely inconsequential, then infant falls should have little effect on their subsequent behaviors. Indeed, in laboratory studies, infants show little evidence of learning from falling. Injurious falls before the lab visit do not distinguish infants who cross a "visual" cliff or real cliff from infants who do not (for review, see Adolph, Kaplan, & Kretch, in press). Novice walkers fall repeatedly on back-to-back trials over large drop-offs, steep slopes, and narrow bridges in laboratory studies (Adolph & Robinson, 2015), and relatively experienced walkers fall repeatedly on back-to-back trials on slippery ground (Adolph, Joh, & Eppler, 2010) or a deformable foam pit (Joh & Adolph, 2006). Similarly, during everyday play, infants' falls may be so unremarkable that they do not alter subsequent behavior.

Current Study

Here, we used infant falls as a model system to understand the impact of errors in early development. We tested the hypothesis that most infant falls are not especially salient to infants or caregivers due to infants' manner of falling and body characteristics. Therefore, low-cost falls do not alter infants' subsequent behaviors and do not provide negative feedback that dissuade infants from practicing.

First, we characterized the *severity* of infants' everyday falls. The centerpiece of our study was a microanalysis of spontaneous infant falls from a large video corpus of free play in the laboratory (Figure 1A, tiers 4–5). In addition, parents retrospectively reported infants' prior history of notable falls (Figure 1A, tiers 2–3). We predicted that most falls are relatively inconsequential to infants and caregivers.

Second, we explored effects of several factors on fall severity. *Developmental* factors—infants' age and walking experience—could increase, decrease, or play no role. Falls may be more severe for older, more experienced infants due to greater body mass, faster speed, and more engagement in risky activities. Alternatively, falls may be less severe for older, more experienced infants because they are better able to avoid serious falls and/or to recover balance before body impact. We also tested whether fall severity depends on *contextual* factors—fall height, fall posture, and movement speed. Epidemiological research suggests that fall severity should increase with fall height (Peden et al., 2008), but no research directly examined effects of fall posture or movement speed on infant falls.

Third, we examined potential *mitigating factors*—behavioral and body factors that diminish fall impact—with no expectation that infants deliberately intend to lessen the consequences of their falls. Given the lack of previous work, we were agnostic about whether infants would display reactive behaviors after losing balance, and whether the sequence of impacts would privilege the torso and head. We measured infants' body dimensions and movement speed to estimate the potential energy generated by falls. Of course, infants' smaller bodies and slower speeds create less potential energy relative to adults; the question is how much less.

Finally, we determined the effect of falling on infants' *subsequent behavior*, in particular whether falling dissuades infants from engaging in activities implicated in the fall as it does for elderly adults. We compared time in motion, interactions with objects, and visits to elevations before and after each fall. We also examined differences in overall locomotion between infants with and without a prior history of notable falls outside the laboratory. Based on previous work, we predicted no change in infants' behavior (e.g., Joh & Adolph, 2006).

Method

We shared video recordings of infants' free-play sessions and coding spreadsheets on Databrary.org (Databrary.org/volume/1042) in accordance with parents' permission. Video clips illustrating the procedure and camera views (Databrary.org/volume/1042/slot/44743) and infant falls (Databrary.org/volume/1042/slot/46744, databrary.org/volume/1042/slot/45029, and databrary.org/volume/1042/slot/44739) are publicly available. In addition, the coding manual and coding scripts (Databrary.org/volume/1042/slot/44651) and exported data and analysis scripts (Databrary.org/volume/1042/slot/44646) are publicly shared.

Participants

We created a video corpus by culling data from three laboratory studies of infant free play (shared at Databrary.org/volume/89, Databrary.org/volume/83, Databrary.org/volume/140). The selection process was blind to infant behaviors. We selected 67 infants in a cross-sectional study; and we selected one session from 94 infants from two longitudinal studies (to equalize each infant's contribution) based on infants' test age and sex (to balance these factors across the dataset). The pooled dataset consisted of 161 infants. Then, 85.71% of infants were included because they fell at least once during the session. The resulting dataset comprised 563 spontaneous falls produced by 138 13-, 15-, and 19-month-old walking infants (± 2 weeks; 67 boys); Figure 1B. Each infant contributed 1–16 falls (M = 4.08 falls, Figure 1C). Families were recruited from the New York City area and received travel reimbursement and small gifts for participation. Infants in the final sample were white (48.55%), black (4.35%), Asian (2.90%), multiple races (16.67%), other (12.32%), or not reported (15.22%); 34.06% were Hispanic. All infants were born at term with no known disabilities.

Parents reported infants' walking experience and fall history. We determined walking experience based on the first day caregivers saw infants walk 3 meters independently without stopping or falling; caregivers used calendars and cell phone photos and videos to corroborate their reports. Walking experience ranged from 2 days to 9.01 months (Figure 1C), and was related to infants' age at test, $r(135) = .72$, $p < .001$ (walking experience was unavailable for one infant). Parents also reported whether infants experienced any notable, self-generated falls (Figure 1A, tiers 2–3) that caused everyday injuries (cuts, bruises, bumps, scrapes, and so on), or more serious injuries that instigated a call to the pediatrician or a medical visit. We included only falls due to infants' own activity (rolling, crawling, walking, etc.) and excluded falls due to caregivers or siblings (e.g., dropped/pushed infant).

Procedure

Infants were observed during spontaneous activity in a large laboratory playroom (5.97 m × 9.42 m) during one 20-minute free-play session. As illustrated in Figure 1D (left panel), in 82 sessions, the room held a couch and elevations (two staircases, small riser-slide, two platforms, one pedestal, *M* height = 30.67 cm, range = 10 – 55 cm; red regions in figure) and several small toys (car, toy apple, plush dog, jingle ball, xylophone, toy saxophone). As illustrated in Figure 1D (right panel), in 56 sessions, the room had no furniture or elevations (only flat ground); in 34 flat-ground sessions, the room had several toys designed to elicit locomotion (large ball, bucket of small balls, push toy, broom, baby-doll stroller), and in 22, the room had no toys.

To examine caregiver's response to infant falls, we observed two types of caregiver behaviors that reflect the normal ebb and flow of everyday life: Sometimes caregivers focus attention on their infants, but sometimes they are occupied with chores or work and largely ignore infants' bids for attention. In the flat-ground playroom, caregivers sat at the edge of the room filling out forms and were instructed not to interact with infants. In the elevation playroom, we told caregivers to interact normally with their infants and to ensure infants' safety while they climbed on furniture and elevations. For ethical reasons, we did not have sessions with elevations and no caregiver interaction. The elevation playroom also had a large flat ground space (gray regions in Figure 1D) and we observed substantial numbers of falls when caregivers interacted with infants on flat ground (189/382 falls in the elevation playroom). Therefore, we observed elevation falls with caregiver interaction and floor falls with and without caregiver interaction.

An experimenter recorded infants' activity with a handheld camera from the perimeter of the room and did not interact with infants or caregivers. Three fixed cameras provided side and overhead views. Babies wore a t-shirt and diaper, so their limb movements were clearly visible. At the end of the study, the experimenter measured infants' recumbent height and nude weight.

Video Coding

Coders scored falls from video using Datavyu, a computerized coding software (www.datavyu.org) that provides frame-by-frame analyses and time-locks user-defined events to the video. Falls were all instances when infants lost balance and could not recover on their own, including falls on the floor, on/off elevations, and falls when caregivers caught them.

Happily, none of the falls in our laboratory resulted in injuries, so we gauged fall *severity* based on whether infants "fussed" (negative vocalizations/facial expressions or crying), caregivers showed concern (moved toward infant, picked up infant, soothed/comforted infant, or asked if infant was alright), and how long it took infants to "recover" and return to play (time from last body impact to when infants resumed normal activity by sitting or standing up, or engaging with toys; see timeline in Figure 1E top panel, and video at databrary.org/volume/1042/slot/46744). Thus, coders did not score recovery time for 24 falls when caregivers "caught" infants before their bodies impacted the ground. If caregivers pulled infants up from the floor after a fall or held them, recovery time was scored at the moment when infants were upright on the floor.

To investigate fall severity across contexts, coders scored fall height (from higher to lower surfaces or on same level), fall posture (upright or in lower crawling/kneeling postures), and movement speed (standing, walking, or running). Fall height was coded for the entire dataset (563 falls). Fall posture was coded only for the 370 floor falls because elevation falls occurred frequently in transitions between postures. Movement speed was coded only for the 351 floor falls when infants were upright because infants did not typically walk or run on elevations. Coders also scored "advanced" behaviors that preceded falls (running, spinning, jumping, climbing on/off elevations without holding caregiver's hands) for all 563 falls.

We tested behavioral factors that mitigate fall impact in the subset of 351 upright floor falls (to avoid confounds of body posture and elevations on reactive behaviors and body impacts). Two upright floor falls were excluded because caregivers caught infants. Thus, we analyzed 349 falls for reactive behaviors, fall direction, and body impact sequence. As shown in the timeline in Figure 1E, coders micro-analyzed the timing of falls by identifying the video frame for the initial loss of balance. Then coders scored *reactive responses* prior to full-body impact: number of reactive steps after losing balance; knee flexion in landing; bracing by grabbing nearby supports; and arresting a fall with outstretched hands before head or torso impact. Coders also scored *fall direction* (forward, backward, or sideways), and the *sequence* of body impacts: the time moment of the first and last body impact, and each body part that impacted the floor (hands, legs, arms, buttocks, torso, head). When two or three body parts impacted the floor simultaneously, coders gave them the same order in the sequence.

To investigate whether falling caused infants to change their subsequent behavior, we analyzed *activity before and after each fall*—time in motion, percent of time playing with objects implicated in the fall, and percent of time on elevations implicated in the fall during each 30-second time window (0–30s, 30–60s, 60–90s, 90–120s, 120–150s, 150–180s) before and after each fall. To determine the amount of locomotor activity, coders identified the beginning and end of each locomotor bout (as in Lee, Cole, Golenia, & Adolph, 2018). Coders scored the duration of interaction with objects infants fell with, and the duration of time on elevations where falls occurred. We included 181 falls from flat-ground sessions in analyses of time in motion (falls in elevation sessions were excluded because coders could not reliably score bouts on elevations), 98 falls for object interactions (falls without objects were excluded); and 162 falls for elevation visits (falls on flat ground were excluded). To analyze the unique consequence of each fall, comparisons before and after falls for each time window were limited to falls that occurred in isolation within the time window. For example, if a second fall occurred 70 seconds after the target fall, the target fall was included in analyses of 0–30 seconds and 30–60 seconds before and after the fall, but no other time windows. To further investigate infants' movement activity after they fell, coders identified the period of no locomotion after infants fell (final segment in Figure 1E, top panel) and, as a comparison, the period of no locomotion after infants deliberately transitioned to the floor (final segment in Figure 1E, bottom panel) for the group of infants who incurred falls included in the analysis of time in motion.

To assess inter-observer reliability, a second coder independently scored 100% of each infant's data for falls, fall severity, fall context, and mitigating factors. The second coder also scored 25% of each infant's spontaneous activity for time in motion, object interaction, and elevation visits. For categorical measures, percent agreement ranged from 85.29% to 99.65%; Cohen's κ = .75 to .99, *p*s < .001. For continuous measures, *r*s = .83 to .99, *p*s < .001. Disagreements between coders were resolved through discussion or by a third coder.

We used generalized estimation equations (GEEs) to account for the clustering effects in the dataset (Hardin & Hilbe, 2003), such as falls contributed by the same infant. The distribution of recovery time was positively skewed, so we log-transformed recovery time to discount effects of influential data points. Preliminary analyses showed no sex differences for fall severity, all χ^2s < .63, *p*s > .43, so we combined data for boys and girls in subsequent analyses.

Results

Fall Severity

Prior falls at home.—Caregivers' reports of notable falls (tiers 2–3 in Figure 1A) showed that 32.61% of infants incurred injuries from falling over the entire period of independent mobility; 4 infants had two such falls. A subset of 11.59% of infants (16 falls) incurred injuries caregivers deemed serious enough to warrant a call or visit to a doctor, but only 3 falls (2.17% of infants) required medical treatment (two fractures, one cut). Note only the subset of 16 falls could have been recorded in a medical database and only the 3 falls requiring medical treatment might have been included in epidemiological reports of infant fall severity.

Falls during laboratory free play.—Falling was frequent during infant free play in our playroom, but largely uneventful (Figure 1A, tiers 4–5). As predicted, after falling, infants rarely fussed, caregivers rarely showed concern, and infants were back at play within a few seconds (Figure 2). As shown by the long green bar in Figure 2A, 90.76% of falls were uneventful. Fussing was limited to 24 (4.26%) falls: 4 falls from the stairs or slide; 7 slips/trips on the floor; 10 babies who were already fussing prior to the fall, and 3 falls that instigated a secondary injury (e.g., infant fell, caught finger in toy car, and hurt finger).

As shown in Figure 2A (inset), caregivers displayed concern on only 7.64% of infant falls. Caregiver concern and infant fussing were correlated, $r(561) = .44$, $p < .001$. However, caregivers expressed concern on 4.97% of total falls when infants did not fuss—when infants climbed on/off elevations (17 falls), ran and fell with a loud impact sound (8 falls), or for unrecognizable reasons (3 falls). On 1.60% of total falls, caregivers did not express concern when infants fussed—they encouraged infants to return to play (8 falls) or appeared not to notice (1 fall). Caregiver concern was more frequent in sessions when caregivers played with infants (9.16% of falls) compared to sessions when caregivers did not (4.42% of falls), $\chi^2 = 4.42$, $p = .04$, but did not differ between elevation and floor falls in the elevation room, $\chi^2 = .07$, $p = .80$. The difference likely reflects the differential attention of caregivers to infants in everyday life.

After falling, infants returned to play within $M = 1.84$ s (range = 34 ms to 63.10 s); timeline in Figure 1E (top panel), and histogram in Figure 2B. For 90.70% of falls, infants resumed normal activity in less than 3 s. Extended recovery times (> 10 s) were limited to 9 falls (extended tail of Figure 2B), 8 of which involved both infant fussing and caregiver concern (top purple symbols in Figure 2C), and 1 that involved neither (top green symbol in Figure 2C). Recovery time did not differ for falls when infants fussed without caregiver concern ($M = 3.53$ s, red symbols in Figure 2C) and for falls when caregivers showed concern without infant fussing ($M = 2.27$ s, blue symbols in Figure 2C), $\chi^2 = 2.37$, $p = .12$; recovery time for falls with no fussing or concern ($M = 1.21$ s) was shorter compared to other situations, χ^2 s > 23.61, *p*s <.001; and recovery time with both fussing and concern ($M = 20.56$ s) was longer compared to other situations, χ^2s > 27.82, *p*s <.001; overall $\chi^2 = 220.78$, $p < .001$.

Factors Influencing Fall Severity

Developmental factors.—Fall severity was largely unrelated to developmental factors. Walking experience did not predict infant fussing, caregiver concern, or duration of recovery time, χ^2s < 2.69, *p*s > .10. Similarly, infant fussing and recovery time did not change with infants' age, χ^2s < 1.00, *p*s > .32. However, caregivers were more likely to express concern for older infants, $\chi^2 = 4.53$, $p = .03$, possibly because older infants were more likely to engage in advanced activities (e.g. climbing slide without caregiver support), $\chi^2 = 39.26$, $p < .001$. Engagement in advanced activities significantly increased caregiver concern, $\chi^2 = 14.45$, $p < .001$. After entering both age and advanced activities, the effect of age on caregiver concern disappeared, $\chi^2 = .26$, $p = .61$, but the effect of advanced activity remained, $\chi^2 = 7.97$, $p = .005$.

Fall context.—Given the small proportion of falls that caused either infant fussing or caregiver concern in each fall context, we collapsed these two measures of severity together to increase power. Only fall posture affected severity. Infant fussing and/or caregiver concern were more frequent and infants' recovery time were longer for falls from an upright posture than low-to-the-ground postures, χ^2s > 4.94, *p*s < .03. But falling from elevations and movement speed did not influence fall severity, χ^2s < 3.12, *p*s > .08.

Mitigating Factors

Reactive behaviors.—Infants spontaneously took reactive steps, flexed their knees, braced with nearby supports, and outstretched their hands to arrest the fall (see exemplar fall in Figure 3A and video at databrary.org/volume/1042/slot/45029), and reactive behaviors were consistent across development. Infants responded rapidly, on average 368.54 ms (*SD* = 211.93) after losing balance and before body impact (timeline in Figure 1E, top panel), typically with a combination of multiple reactive behaviors (Figure 3B). For the majority of upright floor falls (95.99%), infants displayed two or more reactive behaviors. In 66.48%, infants took 1–5 quick reactive steps in an effort to regain balance (Figure 3C). In 99.43%, infants flexed their knees prior to impact. In 13.47%, infants braced themselves with a nearby support. In 90.83%, infants outstretched their hands to arrest a fall before head and torso impact (Figure 3D). Reaction duration, number of reactive behaviors, and likelihood of taking reactive steps, flexing knees, bracing, and outstretching hands did not change with age or walking experience, χ^2s < 3.12, *p*s > .08.

Fall direction and sequence of body impacts.—As shown in Figure 4, forward falls were more frequent (61.03%) than backward (29.23%) and sideways falls (9.74%). Each bubble string shows a sequence of body impacts; all sequences that comprised >1% of falls and all that involved head impact are represented; the area of the bubbles in each string reflects the relative frequency of the sequence (out of all falls in the dataset).

Generally, head/torso impacts were more serious than impacts for other body parts. Head/torso impacts were related to fall severity, χ^2s > 10.19, *p*s < .001. However, initial impacts of "safer" body parts can break a fall prior to head/torso impact. The predominance of "cool"-color bubbles (hands, legs, buttocks, arms) in Figure 4 indicates that most falls were onto safer body parts. Across fall directions, hand impacts were most frequent (91.12% of falls), followed by leg (70.77%) and buttock impacts (49.00%), and occurred early in the sequences. Most falls were quickly arrested by early body impacts. The time between first and last body impact averaged 226.05 ms (*SD* = 225.62); see timeline in Figure 1E, top panel. Most falls had one (27.51%), two (51.00%), or three (18.05%) body impacts. Infants caught themselves with their hands within *M* = 451.73 ms (*SD* = 241.46) after losing balance (Figure 3D) and 62.46% of falls were effectively ended by hands with no further impacts. Thus, torso (6.88% of falls) and head impacts (3.15% of falls) were rare, as shown by the scarcity of "warm"-color bubbles. In addition, a sequence of impacts mitigates potentially injurious forces for the final body part. That is, a direct fall onto the torso incurs a greater impact to the torso than a fall that involves hands, legs, and buttocks prior to torso impact. Likely due to infants' body posture when they lost balance and flexed knees and outstretched hands moments later, torso and head impact occurred toward the end of a sequence of multiple impacts (see warm-color bubbles at end of strings). Infants had longer recovery time and caregivers showed more concern for sideways falls than backward falls, χ^2s > 4.61, *p*s < .03 (but not compared to forward falls). The probability of infant fussing did not differ between fall directions, $\chi^2 = 2.06$, $p = .36$.

Body size, speed, and potential energy.—Infants' small bodies and slow walking speeds limited the amount of potential energy. As shown in Figure 5A, compared with the average U.S. adult, who is 168.55 cm tall and weighs 83.6 kg (Fryar, Kruszon-Moran, Gu, & Ogden, 2018), infants were short (*M* height = 78.66 cm, range = 69.80 – 90.75) and thus close to the ground; infants were also lightweight (*M* weight = 10.46 kg, range = 7.64 – 15.21), and therefore had less mass to produce potential energy. In addition, infants moved slowly, averaging 46.07 cm/s in free play (Lee et al., 2018). In comparison, the average adult walks three times faster than infants (R. W. Bohannon, 1997).

We estimated the amount of potential energy generated by a fall based on infant's weight and the height of their center of mass for standing falls (Hayes et al., 1993), and incorporated their speed for walking and running falls. The potential energy generated by infant falls (M = 46.55 Joules, SD = 7.61) was about 18 times less than if infants were adult sized and walked at adult speeds (M = 857.93 Joules, SD = 36.03, Figure 5B).

Impact of Falling on Subsequent Activity

Short term deterrence of falling.—As we suspected, infants did not decrease their movement or shy away from objects (e.g., toy stroller) or elevations (e.g., slide) associated with falls—or at most, decrease in movement was brief. Figure 6A shows the accumulated time in motion over each 30-s time window before and after a fall, with falls defined from the moment of lost balance to the moment of recovery when infants returned to play (Figure 1E, top panel). Only the first 30-s time window showed a decrease in movement relative to the 30-s window before the fall, χ^2 = 23.71, p < .001; all other time windows, χ^2s < 1.85, ps > .17. Albeit significant, the "dip" in movement was slight—M = 3.41 less than the 30-s time window before the fall.

However, the dip disappeared if we began counting post-fall time windows at the moment when infants re-initiated locomotion (last event in Figure 1E, top panel) rather than the moment of recovery. That is, when we excluded no-locomotion periods following falls, the decrease in time in motion disappeared for every time window, χ^2s < 1.88, ps > .17 (Figure 6B). Thus, the dip in movement resulted from inclusion of the no-locomotion period after infants returned to play, and time in motion did not decrease after infants resumed locomotion.

To further test the notion that falls are an undesired interruption to locomotion but not a deterrence to further locomotion, we compared no-locomotion periods after falls to periods when infants deliberately stopped moving. Indeed, no-locomotion periods were *longer* after falling (M = 5.91s, SD = 9.66) compared to when infants deliberately stopped walking but remained upright (M = 2.97s, SD = 3.53), t(7246) = 10.23, p < .001, suggesting that the time to get up off the floor has cost. But no-locomotion periods were *shorter* after falling compared to when infants deliberately transitioned to the floor (M = 15.24, SD = 25.06; last segment in Figure 1E, bottom panel), t(531) = 4.82, p < .001, suggesting that falls were not a deterrence to further locomotion.

In addition, infants did not avoid objects or elevations implicated in falls. Time with fall-associated objects and elevations did not differ in any time window, χ^2s < 2.07, ps > .15 (Figure 6C and 6D).

Long-term effects of falling.—Prior notable falls reported by caregivers did not suppress infants' movement in the lab session. The average time gap between the occurrence of a notable fall and the test date was 4.6 months (range = 1 day to 14 months). In fact, infants with a history of notable falls tended to take more steps/hour (Ms = 3722.81 vs. 3288.01 steps), t(136) = 1.93, p = .06, and spend more time in motion (Ms = 26.25 vs. 23.78 min per hour), t(136) = 1.87, p = .06.

Discussion

What is the impact of errors in infant development? Falling—errors in balance and motor control—is an ideal model system to address this question because falling is a natural, frequent event that is tangible for infants and directly observable for researchers. We found that everyday infant falls are such low-impact, low-cost events that they go largely unmarked. Most infants did not incur notable falls during the entire period of independent mobility, and babies rarely fussed, caregivers rarely showed concern, and infants returned to play within a few seconds after falling in free play. Impact forces were mitigated by a suite of behavioral and body factors “built” into the system—infants’ slow movement speeds and small bodies, quick reactive responses to loss of balance, and effective arrest of the fall before risky body impacts. Likely due to the low cost of falling, infants were not deterred from engaging in the same activities implicated in the fall.

Low impact errors in infant development

Early in development, most errors may entail low impact and low cost. In fact, for basic skills such as walking and talking, the system may be “designed” (via body characteristics, social supports, environmental constraints, etc.) to mitigate the cost of errors. When infants are learning to talk, mispronounced words and speech dysfluencies go largely uncorrected, receive little explicit negative feedback, and do not deter attempts to communicate (e.g., J. N. Bohannon & Stanowicz, 1988). Similar to speech errors that mostly result in a brief postponement in communication, most errors in walking incurred only a brief interruption of ongoing activity.

We are the first to reveal a complete pyramid of fall severity. Extending beyond the top two fall tiers that result in infant death and serious injury (2% of infants in our parent-report data and 3% of infants in the United States, Borse et al., 2008), we documented a third tier of falls that caregivers remember weeks or months later because infants incurred minor injuries such as cuts and bumps (30% of infants in the parent-report data). The fourth tier comprises falls that do not incur injury but draw attention in the moment because infants fussed or caregivers expressed concern (9% of falls in the video corpus). The bottom tier constitutes the dozens of unimpactful falls (91% of falls in the video corpus) that infants experience every day (Adolph et al., 2012).

As a model system for understanding the impact of infant errors, our analyses of fall severity suggest that a robust system can render errors trivial in most everyday contexts. As expected, falls while infants were upright resulted in more infant fussing and/or caregiver concern than falls while infants were in low-to-the-ground postures. However, the vast majority of falls while upright did neither.

Possibly, our subsample of salient video falls was too small to detect effects of fall context. However, the “salient” falls in our dataset are not meaningful for epidemiologists or health professionals. Moreover, in addition to fall height, which is a robust predictor of fall severity in epidemiological research, the top-tier falls that are meaningful for understanding serious fall injuries might be related to a confluence of factors. Perhaps infants without sufficient walking experience to gauge risk of falling from a high elevation (e.g., Kretch & Adolph, 2013a, 2013b) are overly represented in epidemiological reports if their caregivers are momentarily inattentive and environmental safeguards are missing. Indeed, infants younger than 12 months have a higher fall mortality rate than other age groups in low- and middle-income countries, but not in high-income countries (Peden et al., 2008).

Moreover, increased caregiver concern for older infants likely resulted from babies engaging in advanced, challenging activities. With age, children's increased skills and engagement in advanced activities generate new types of risk. Indeed, teenagers incur a higher proportion of falls from a height and thus increased danger from falling compared with other age groups, due to engaging in riskier behaviors such as climbing trees (American Academy of Pediatrics, 2001; Peden et al., 2008). However, during infancy, babies' skill level is low compared to adolescents. Therefore, infants are protected by their *lack of skills* from engaging in behaviors that pose real danger.

Collaborative Factors that Mitigate Impact Forces

Several behavioral and body factors collaborate to mitigate fall impact forces. Apparently, infants are like natural Judo practitioners. Like a martial artist "receiving ukemi," infants' behavioral reactions mitigate impact forces. As they begin to lose balance, infants frequently take reactive steps (keeps body upright longer), flex their knees during landing (decreases impact forces), and grasp available supports (reduces fall speed). When they impact the ground, infants frequently arrest the fall with their hands, and they mostly fall forward onto hands and legs or backward onto legs and/or buttocks, where skin, fat, and muscle have a high capacity to absorb potential energy (Butte, Hopkinson, Wong, Smith, & Ellis, 2000). Torso and head impacts are rare and always occur after earlier body impacts, so the energy is distributed and absorbed before the torso or head hit the ground. Thus, the transmitted residual energy rarely exceeds the threshold of infants' malleable, robust bones (Currey, 1979). In addition, infants' short bodies are close to the ground, their mass is small, and they move slowly, so the potential energy generated by the fall is small.

When accurate affordance perception and explicit reasoning about causes and consequences of falling are not yet formed (Kretch & Adolph, 2013a, 2013b), protection against high-penalty falls in early development can be "outsourced" to infants' spontaneous behaviors and bodies. Unlike trained martial artists who *deliberately* fall in particular ways to mitigate impact, we have no reason to believe that infants intentionally plan their reactive behaviors to mitigate fall impact. Instead, the mitigating effects of reactive behaviors are likely the *inadvertent* result of infants trying to regain balance. Indeed, we observed the same reactive behaviors at the same rates across the entire range of age and walking experience.

As in "soft robotics" (Pfeifer & Bongard, 2007), "smart" solutions can be outsourced to infants' bodies, not their brains. Thus, infants' effective sequence of body impacts likely result from the biomechanics of their body position as they lose balance, rather than a deliberate choice to mitigate fall impact. The same is likely for elderly falls, but with their larger body mass and failure to effectively arrest the fall, elderly people are more likely to incur hip, torso, and head impacts. Infants' small, squishy bodies, and slow movement speeds help to explain the different outcomes for infant and elderly falls. Infants embody all the factors that elderly people lack. Indeed, fall-training programs for elders often obtain limited improvements (e.g., Chang et al., 2004).

In addition, infants receive social support during everyday activity that elderly people lack. Whereas elders are likely unaccompanied as they go about their day, in our dataset, caregivers hovered nearby to catch infants when they lost balance on elevations. Finally, environmental safeguards prevent serious falls, including window guards, stair gates, crib rails, and padded playground surfaces (e.g., Spiegel & Lindaman, 1977).

Such collaborative protective factors exist exclusively in early stages of development. Later in development, when reaction times are slow, bodies are large, bones are brittle, and caregivers are unavailable, errors are more costly, and higher-order psychological functions are required to avoid mishaps. In the absence of inbuilt protective factors, older children and adults must learn to perceive possibilities for locomotion, make accurate decisions, and associate errors with their causes if they are to avoid falling.

Implications for Learning and Development

It seems reasonable to assume that infants learn from their mistakes and alter subsequent behaviors based on negative feedback. And frequent falls provide immense opportunities for infants to learn. However, a history of self-induced, notable falls was related to more, not less, locomotor activity. During free play, infants did not decrease their locomotor activity after they resumed prior movement interrupted by a fall. Nor did infants avoid interacting with objects and elevations implicated in their falls. One infant fell 15 times with the same stroller in 20 minutes of play. She returned to pushing the stroller despite falling repeatedly, including the thirteenth fall that involved torso and head impact and caused her to cry and her caregiver to show concern (see video at databrary.org/volume/1042/slot/44739). The transient, small dip in movement duration in the first 30-s time window after a fall likely reflects an unexpected interruption of ongoing activity and the time to transition to the original upright posture rather than an aversion to locomotion. Moreover, previous work showed that infants do not avoid obstacles such as large drop-offs, steep slopes, and narrow bridges after falling on previous trials (Adolph, 1995, 1997; Kretch & Adolph, 2013a, 2013b). Similarly, infants fall repeatedly into a foam pit or on a slippery patch of ground on more than a dozen consecutive trials (Adolph et al., 2010; Joh & Adolph, 2006).

Why might infants display no behavioral changes in the amount of movement, object interaction, and elevation visits after falls during free play? Possibly, infants do not register the factors that led them to lose balance before a fall, and so do not associate falls with the environmental factors that caused them to fall. Instead, infants may learn to walk by noticing the body-environment factors that allow them to get somewhere and to achieve their goals (Hoch et al., 2019). An analogous “reinforcement learning” model in artificial intelligence would heavily weigh positive rewards but render negative feedback inconsequential. Even if infants recognize that certain activities, objects, or elevations are challenging for balance control, infants may have low motivation to change their behaviors due to the low cost of falls and/or high reward of walking and playing. Another possibility suggested by “optimism in the face of uncertainty” in artificial intelligence (Szita & Lőrincz, 2008) is that infants purposefully return to scenarios with high uncertainty—that is, the type of activity that led to falls—to learn actions not yet mastered.

Regardless, low-cost, low-impact falls do not deter infants from obtaining the immense amounts of practice required to learn to walk, likely the real key for learning generative skills. Infants' walking skill and ability to safely navigate obstacles increases dramatically over the first 6 months after walk onset—each day filled with thousands of steps on dozens of surfaces and involving countless decisions about whether and where to go (Adolph & Hoch, 2019; Adolph & Robinson, 2015). Immense practice is necessary for infant walking to become sufficiently controlled, generative, and flexible to allow infants to move through the everyday environment on their own. Little deterrence from low impact errors in early periods of development may encourage infants to keep practicing basic skills. Later in development when errors entail high physical and social impact, deterrence from practice makes it harder to learn skills such as ice skating and speaking a second language.

Conclusions

We propose that basic skills such as walking and talking are generally robust to errors in early stages of development. In fact, development may be so robust that errors do not dissuade infants from obtaining the immense amounts of practice necessary to master basic skills. Put another way, the low impact of errors on infant behavior is highly adaptive by ensuring continued exploration and learning. A system that allows frequent, low-impact errors encourages beginners to keep practicing to the point of mastery.

Acknowledgments

This research was supported by NICHD Grant R01- HD033486 and DARPA Grant N66001-19-2-4035 to Karen E. Adolph, and by a grant from the NYU Dean's Undergraduate Research Fund to Hannah Borenstein. Portions of this work were presented at the International Society for Developmental Psychobiology in November 2017, the International Congress of Infant Studies in June 2018, and the Society for Research in Child Development in March 2019. We thank Alan Fern, Todd Gureckis, Justine Hoch, Stephen Robinovitch, and Catherine Tamis-LeMonda for their insightful comments; Mark Blumberg for help with figure design; Justine Hoch and Patrick Shrout for advice on statistical analyses; Hannah Borenstein for her important contributions to video coding; Zahin Ahmed, Minxin Cheng, Christopher DeCamp, Lorraine De Velez, Omar El Fadel, Shohan Hasan, Carli Heiman, Orit Herzberg, Justine Hoch, and Yueqiao Liu for assistance with video coding; and the members of the NYU Infant Action Lab for data collection. The authors declare no conflict of interest.

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Research Highlights

- Similar to errors in talking, errors in walking—that is, falling—are low-cost, low-impact events in early stages of development.
- After falling, infants rarely fussed, caregivers rarely showed concern, and infants immediately returned to play—typically with the same level of activity prior to the fall.
- A suite of collaborative, protective factors—effective reactive behaviors, quick arrest of falls, and infant's small bodies—mitigated the impact forces of falling.
- A system that discounts errors ensures that infants obtain the immense amounts of practice required for learning early in development.

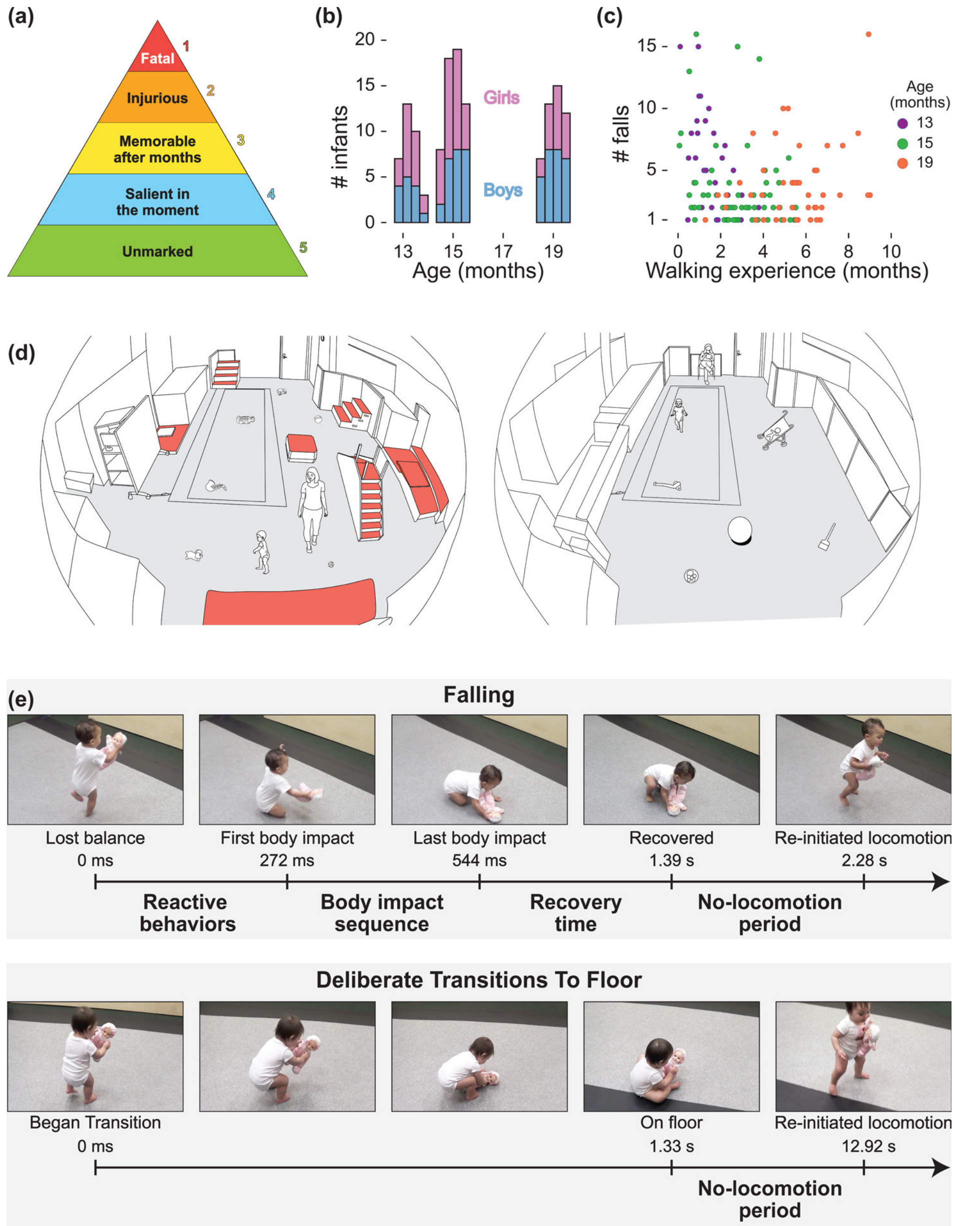

Figure 1.

Conceptualization of fall severity, method, and data coding. (A). Pyramid of fall severity. Tiers 1–2 represent epidemiological research based on medical reports of death, hospitalization, and out-patient medical care. Tier 3 represents our parent reports of minor injuries. Tiers 4–5 represent our coding of real-time infant and caregiver responses to infant falls. (B). Number of boys and girls who contributed at least one fall across age (total N = 138). (C). Number of falls contributed by each infant (M = 4.08) by walking experience. Symbols denote individual infants; colors represent age groups. (D). Fisheye views of laboratory playroom. Left panel shows the room set up with a couch and several elevations (colored in red) and several standard toys. Caregivers were instructed to play with infants as they normally would. Right panel shows the same room with a different set of standard toys but no furniture or elevations (only flat ground). Caregivers sat on the edge of the room and did not interact with infants. A third room set up was identical, but no toys were available. In all three room set ups, the experimenter (not shown) stood at the corner of the room and recorded infants' movements with a hand-held camera. (E) Time course of an exemplar fall (top panel) and a deliberate transition to the floor (bottom panel) from one infant. Top panel: Numbers indicate elapsed time from loss of balance to first body impact, last body impact, recovery and return to play, and re-initiation of locomotion. Bottom panel: Numbers indicate elapsed time from start of transition to the floor, moment body was on the floor, and re-initiation of locomotion.

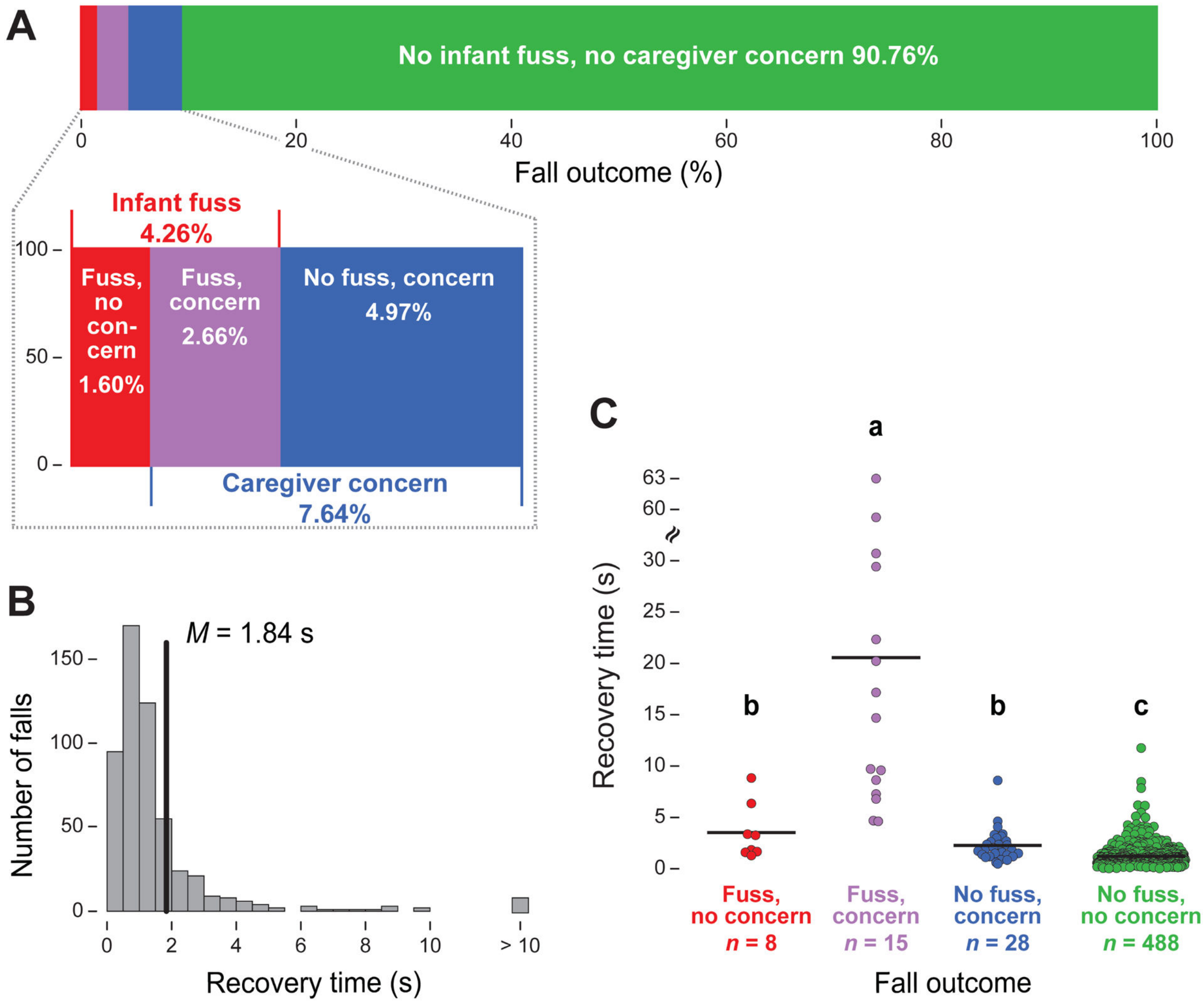

Figure 2.

Measures of fall severity. (A). Infant and caregiver reactions to falls. Top panel and inset: Percent of falls in which infants fussed (red bars), caregivers showed concern (blue bars), both occurred (purple bars), or neither occurred (green bar). (B). Infant recovery time (time for infant to return to normal play activity after a fall). (C). Recovery time when infants fussed, caregivers showed concern, both occurred, or neither occurred. Letters denote significant differences (*p*s < .05) among fall outcomes.

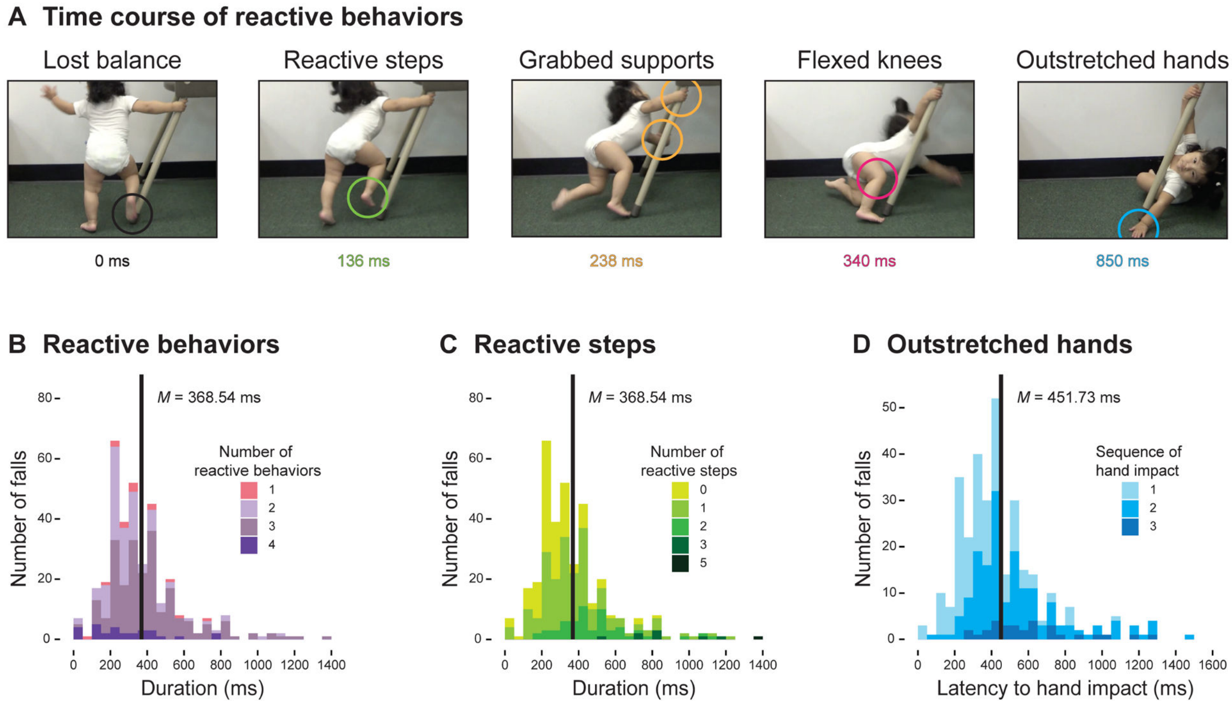

Figure 3.

Infants' reactive behaviors after losing balance. (A) Time course of four types of reactive behaviors after losing balance in one exemplar fall (reactive steps, grabbed nearby supports, flexed knees in landing, and arrested the fall with outstretched hands). Colored numbers indicate the elapsed time from loss of balance to each reactive behavior. (B) Histogram of reactive duration (from losing balance to first body impact) categorized by number of different reactive behaviors (0–4) after infants lost balance. Colors represent the number of different types of reactive behaviors involved in the fall. (C) Histogram of reactive duration categorized by number of reactive steps infants took after losing balance. (D) Latency between losing balance and hand impact. Colors represent the order of hand impact in the entire body-impact sequence (1 denotes hand was the first body part to impact ground, 2 denotes hand was the second body part, etc.).

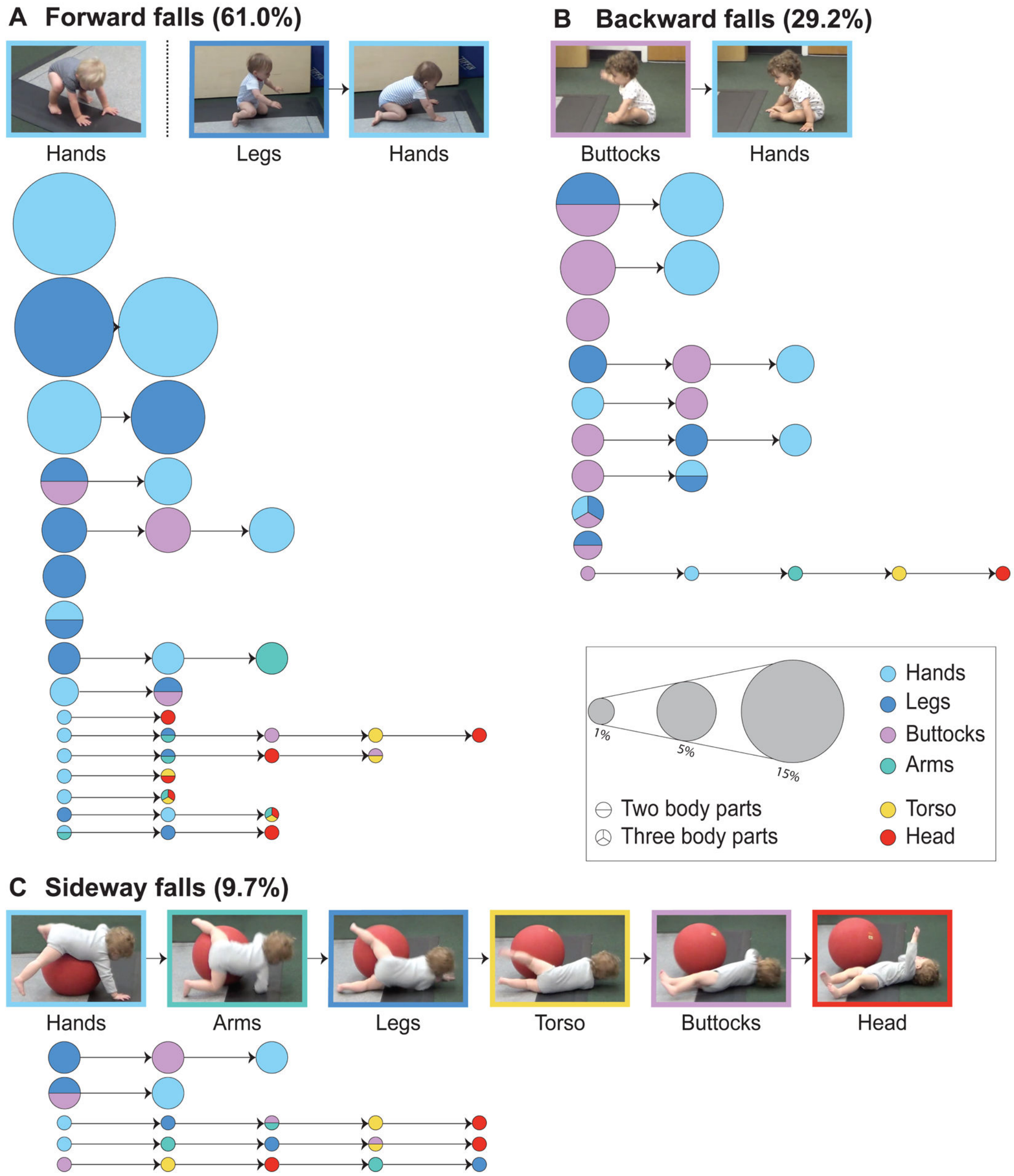

Figure 4.

Sequence of body impacts during (A) forward, (B) backward, and (C) sideways falls. Video frames show the most common body-impact sequences for forward and backward falls and a representative sideways fall. The bubble strings show every observed body impact sequence that occurred in more than 1% of falls and all sequences that involved head impacts. The relative frequency (out of all falls) of each body impact sequence is represented by the area of the bubbles. Each bubble denotes one body impact; bubbles are split in two or three sections to represent simultaneous impact of two or three body parts. Bubble color represents body part involved in the impact ("cool" colors denote less risky body parts, "warm" colors denote more risky body parts).

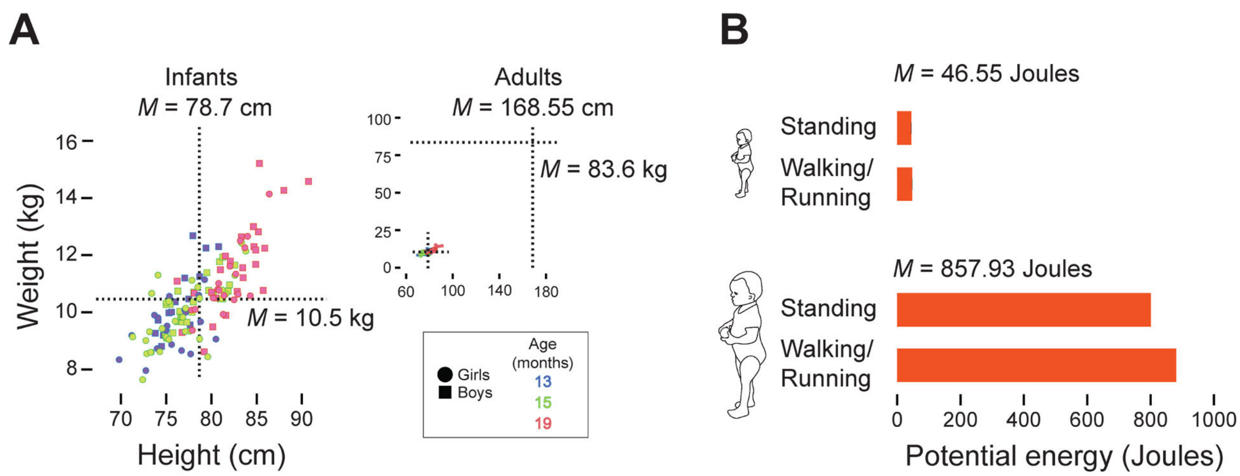

Figure 5.

Infant body factors that mitigate fall impact relative to an average U.S. adult. (A) Height and weight. Scatterplot shows that older infants and boys were generally taller and heavier than younger infants and girls. Inset shows that adults are 2 times taller and 8 times heavier than infants. (B) Potential energy of falls (Joules). Top panel: Average potential energy generated by infants' falls while standing versus walking or running on the floor. Error bars denote standard errors. Bottom panel: Estimated energy generated by falls if infants had the body size and movement speed of an average U.S. adult. Note, adult data taken from the literature.

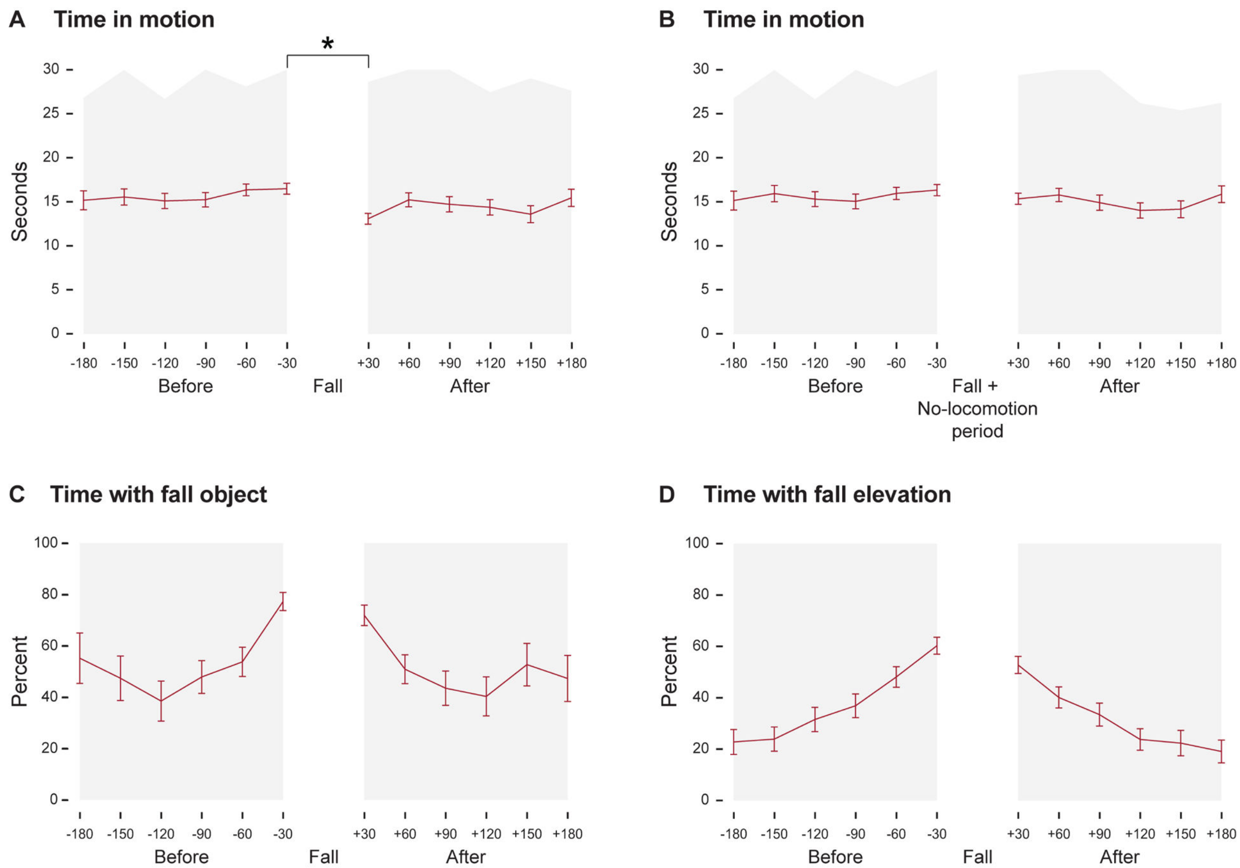

Figure 6.

Activity before and after falling. Data were normalized to each fall in 30-s time windows. All falls included the time from the moment infants lost balance until the time infants recovered balance and returned to play. Post-fall time windows began at the moment of recovery for (A), (C), and (D), and at the moment locomotion resumed for (B). Red lines denote mean activity in each time window. (A-B) Accumulated time in motion. (C) Percent of time interacting with the object implicated in the fall. (D) Percent of time visiting the elevation where the fall occurred. Error bars denote +/− one standard error. Gray areas represent range of activity.