Title

Effects Of Body Weight Support On Crawling Locomotion In Infants

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Publication Date

2023-06-16

EFFECTS OF BODY WEIGHT SUPPORT ON CRAWLING LOCOMOTION IN INFANTS

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A capstone project submitted for Graduation with University Honors

May 12, 2023

University Honors

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ABSTRACT

Training with assistive technology such as partial body weight support (BWS) systems is a popular method used to improve walking gait in adults and older children. The goal of this work was to assess the effects of BWS on crawling gait of infants with and without motor delays. Data from six typically developing infants and two infants with Down syndrome were considered. These data were collected from infants performing overground crawling trials with and without the assistance from a portable BWS system. Two-dimensional position data of the body's center of mass (CoM) in the sagittal plane were obtained from the video recordings using a digitization tool. The digitized data were then used to quantify CoM motion. Kinematic variables were computed using custom programming software. Our preliminary results suggest that both populations can adapt to the BWS immediately as shown by changes in their body movement across conditions. This information increases our understanding of how infants use the assistance from a BWS system to crawl and can be used for the design of long-term BWS interventions to promote crawling in infants with motor delays.

ACKNOWLEDGEMENTS

I’d like to express my sincere gratitude toward Dr. Elena Kokkoni for her guidance and encouragement through this research project. Her expertise and insight helped guide me on how to approach research and gave valuable feedback strengthening my work.

I’d also like to extend my thanks to Tristan McCarty whose valuable support has been crucial to the success of this project. His valuable skills and kindness have helped me to overcome many challenges making this project possible.

I’d also like to thank all the other members of the Pediatric Rehabilitation Lab for their invaluable contribution and support to this project.

Finally, I would like to thank my parents Jennifer and Long Nguyen as well as all my friends for their support and encouragement throughout this process.

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BACKGROUND

Typical Crawling Skill Development

Motor development has been associated with cognitive, perceptual, and language development [1]–[4]. Gross motor skills that typically developing (TD) infants acquire during their first year of life include sitting, crawling, walking, and standing, among others [5]. Crawling, in particular, is the first form of locomotion that allows infants to explore their environment at a very young age, with potentially positive effects on other systems [6]–[9]. For example, crawling enhances the development of spatial search strategies like object permanence [10]. In addition, the onset of crawling locomotion has been associated with neural changes, such as the increase of cortico-cortical connections [11], and increased memory retrieval abilities [12].

The first experiences with crawling emerge at around eight months of age and continue until the onset of walking [13]. During this period, various crawling patterns that are characterized by changes in interlimb coordination are observed [14], [15]. These changes are important to study as they may increase our understanding of how balance and mobility are developed [16]. For example, prior to the onset of hands-and-knees crawling, infants move forward with a more uncoordinated or inconsistent pattern [16]. During this period, most infants move forward with their bellies; this allows for the abdomen to rest on the ground requiring minimal effort with regard to balance, and permitting for the timing of limb movements to be more unconstrained [6]. Over time, however, infants gain proficiency and build arm strength, which eventually leads to the development of reciprocal crawling (i.e., crawling on the hands and knees) [6], [17], [18]. With the onset of hands-and-knees crawling, the abdomen of the infants no longer rests on the ground; instead, infants move forward using their limbs in a diagonal movement pattern and demonstrate more coordinated movements [19], [20]. This stage highlights the flexibility and efficiency of hand-and-knees crawling as a way to move throughout the environment, given that infants continue to develop at many levels during that time [16].

The typical crawling gait of mature crawlers has certain characteristics. As the ipsilateral limbs alternate, a swing phase for retraction and stance phase for protraction of the shoulder and hip are observed, similar to the gait of other quadruped mammals [15], [21]–[23]. The elbow joint is extended during the stance phase, whereas it performs a single flexion and extension during the swing phase allowing for moving the body forward [24]. Regarding the lower limbs, as the leg leaves the ground, flexion occurs at the knee and hip bringing the limb forward where it would then extend and be brought back to the ground; it is then flexed again under the weight of the body but would then extend again to push the body forward [25], [26]. This action of leg propulsion during crawling in infants is also seen in the gait of other quadruped mammals [24], [27]–[29]. In addition, infants place their limbs further away from the body midline (in a wider stance) to allow for a more stable gait; this pattern is similar to how other short-limbed animals adopt their gaits to gain more stability [15], [30], [31]. Lastly, as proficiency increases and the infants' movements become faster and greater, velocity also increases; and locomotion cycle time, swing duration, stance duration, number of cycles, and steps decrease [6]. Although information on crawling patterns in TD infants exists in the literature, there is limited information regarding crawling patterns in atypical infant populations.

Motor Skill Development in Down Syndrome

Delays in motor development early on can have detrimental effects on other developmental systems, such as cognition and language development, for toddlers and school-aged children [1]. Down syndrome (DS) results from an extra copy of chromosome 21 and comes with a variety of physical, mental, and other functional impairments [32]. In contrast to TD infants, infants with DS have motor delays that may be due to the reduced size of the cerebrum, adequate brain maturation, and pathophysiological processes that may take place [33]. Although the sequence of motor skill acquisition in infants with DS is still the same compared to that of TD infants, they require more time to acquire antigravitation skills, such as being able to stand [34]. As they get older, the delays in motor development of children with DS increase further, thus, increasing the gap with their TD counterparts [35], [36]. Additionally, hypertonia seen in infants with DS induces limitations in their movement; this has an effect on their crawling abilities, which are also greatly impacted [37]. In general, children with DS require more time to learn movements as movement complexity in developmental skills increases; as the difficulty of the movement increases, the time taken to attain and learn the skills also exponentially increases [38]. As a result, it is difficult for them to acquire experiences and explore the environment. Nevertheless, practice through training for adequate periods of time can alter the course of their development and enhance motor outcomes in this population [39].

Assistive Technology to Promote Movement

Assistive technology (AT) can maximize opportunities for providing experiences and time for training skills crucial for the development of children with special needs [40], [41]. Various types of AT include adaptive, mechanical or electrical tools, devices, and adapted toys that enable children in learning, mobility, communication, and other activities in both the home and community environments [40], [42]. AT specifically designed to assist with locomotion comes in various forms, such as wheelchairs, walkers, treadmills, and body weight support (BWS) systems [41], [43]–[45]. Use of these types of AT have shown to advance mobility outcomes in populations with motor challenges. For example, previous studies have found that long-term treadmill interventions can lead to an earlier emergence of walking onset in infants with DS [45]–[47]. The authors suggest that this may be true because, during the training on the treadmill, infants have opportunities for practicing the alternating limb movement pattern; this pattern has been suggested to be a common feature shared between stepping on a treadmill and independent walking later on [48], [49]. The repeated opportunities for practice helped to build strength and improve balance, two components that are suggested to be critical requisites for the onset of independent locomotion [50]. Nevertheless, there is a lack of AT designed for enhancing mobility in pediatric populations younger than five years of age, and even among the devices that are available to them, the range of mobility skills that the device targets is limited whereas accessibility to the families for long-term use can be challenging [51]. Portable and more affordable BWS devices, such as the system used in this work, can provide support for a variety of movements, and thus, its use may help with training a range of skills, including crawling.

The goal for using a BWS system during training is to be able to offload a certain amount of the user's body weight in order to overcome the gravitational forces acting on the limbs and facilitate motor activities which would be difficult otherwise. Typically, BWS systems are used in combination with other devices, such as treadmills [41], [52]–[54]. However, research comparing gait on treadmills versus over ground revealed small but significant differences [55]–[57], such as deviations in gait motor patterns and kinematics, leading to the conclusion that treadmill gait may not directly translate to overground gait [58]–[61]. Only a few longitudinal studies on the use of various BWS systems for overground training have been performed with very young populations with mobility challenges [62]–[65]. Thus, research on the use of BWS systems for overground mobility training in these populations should be further investigated.

Biomechanics of Movement

To investigate the effects of AT use on the movement of users, researchers typically use tools from the field of biomechanics. Variables to characterize movement and/or assess change in movement include joint angles, center of mass (CoM) motion, limb movement paths, and muscle activity, among others. Locomotion, in particular, can be characterized through the study of movement of the CoM as the body moves in space [66]. CoM motion trajectories can be obtained from positional data. Based on past studies, the CoM has been found to be approximately a few centimeters in front of the lumbosacral joint [67].

The trajectory of CoM motion is a good summary index of balance and neural maturation in walking and other forms of locomotion [68]. Displacement of CoM characterizes the whole body system and is often used to explain the mechanics during locomotion, metabolic energy expenditure, postural adjustments, and dynamic equilibrium [69]. It also reflects other important biomechanical and physiological variables such as timing of muscle activation and mechanical work done by the body [70], [71]. In adults, an inverted-pendulum oscillation is suggested to exist in order to minimize energy expenditure [72], [73]. However, in toddlers and developing children, the type of mechanisms tends to vary, especially in those with gait impairments [74], [75]. In crawling, diagonal interlimb patterns are the most stable type that allows for the CoM to keep moving forward with minimal destabilizing torques for the CoM shifting side to side [6]. Lateral-sequence gait which is chosen by infants is a stable pattern of coordination that allows for the projection of the CoM to stay within the support polygon, which is the area delimited by the limbs on the ground, keeping the body stable under gravity conditions [24], [76]. Speed of gait has been shown to have an effect on CoM motion in normal gait as well [77], [78]. The effects of BWS on crawling gait of both TD infants and infants with DS have not been adequately explored as most studies primarily focus on healthy infants and mainly look at muscle activity itself and not CoM motion [15].

The study of CoM motion during crawling with BWS assistance can provide insightful explanations on the adaptation and locomotor mechanisms that can be useful for the design of training programs for young populations with mobility impairments. Therefore, the goal of this preliminary examination was to assess the immediate changes in the body movement during crawling with and without the assistance from a BWS system. We hypothesized that changes would be observed with the use of the BWS system.

METHODS

Dataset

The dataset used in this investigation consisted of video recordings of infants performing crawling trials with and without the assistance from a BWS device (for more information on the device, see next section). More specifically, data from six TD infants (Mean age = 10.5 ± 1.2 months) and two infants diagnosed with DS (Mean age = 19.2 ± 0.78 months) were analyzed. All infants in this study had acquired the ability to crawl over large distances, which explains the greater mean age of infants with DS in our sample. Approvals for the collection and analyses of data were provided by the participating institutions.

The experimental protocol used in this study involved three distinct conditions. In the first condition (Pre), all infants performed crawling trials without the assistance from the BWS device; in the second condition (In), infants had the assistance from the BWS device during crawling; lastly, in the third condition (Post), infants performed again crawling trials without the assistance from the BWS device. The amount of BWS used was about 20% of the infants' body weight to allow them to move easier in the horizontal plane. To be able to track the motion of the infants' bodies in space, a circular marker was placed in the middle of the lumbar region of their trunk. This protocol was conducted on two separate non-consecutive days within the same week.

Both sessions were video recorded using three high-definition cameras placed at different locations in space. This setup allowed for the examination of the activities from different viewpoints (side, top, and front views). The frame rate of all cameras was 30 frames per second.

Device

The device used in this study is a commercially available portable BWS system (PUMA®, Enliten, LLC, Newark, DE). The system consists of an overhead canopy with two 10 ft parallel beams as well as a perpendicular moveable 10 ft beam that is connected to a soft wearable harness (My Early Steps™, Little Dundi, LLC). The harness provided support for the trunk but not the limbs. The BWS system allows for vertical and horizontal movement of the user inside of a 100 sq ft area. A counterweight pulley system is connected to the harness in order to manipulate the amount of assistance given to the user by unloading a part of the user's body weight. The counterweight pulley design allows for constant vertical support as the user moves, allowing for a wide range of motor activities overground, including crawling which was the main locomotor activity investigated in this work. The counterweight is also within a confined tube making it so that during the movement of the user, the weight would not swing back and forth which would affect the amount of support for the infant; oscillation in the counterweight would add more force to the unloading force potentially adding more variance to the body's movement [79].

Data Analysis

The major focus of this investigation was on the analysis of body movement during crawling from the video recordings. This analysis consisted of multiple sequential steps. The first step involved the identification of segments that had multiple valid crawling cycles. The reason for this was because the marker placed on the infant's body could not be tracked sometimes due to occlusions, and thus, trials with portions of missing data were excluded from this analysis.

To be able to analyze the crawling segments, a crawling trial had to be defined and get annotated in all videos. The crawling trial onset was defined as the frame where infants would make their first forward motion and their hand was lifted off of the ground, after having all hands and knees touching the ground prior to that. The trial offset was the first frame when the infant had completed the task and their knee touched the ground.

The next step involved tracking of the circular marker on the infants' bodies from both the top and side views. The DLTdv digitization tool [80] was used for this part of analysis. We run this tool in MATLAB (R2021a, The Mathworks Inc., MA). The marker was tracked from the onset to the offset of the trial *(Figure 1)* with the exception of when it was obscured due to beams, limbs, or other confounding factors. The video was also calibrated by getting the length of a floor mat that was in the same plane as the infant during the task in order to more accurately measure the displacements. The x and y coordinates of the marker were then obtained in each frame. Throughout the trial, there would be various moments where the infant would stop crawling such as to observe their environment, move far off the path which would affect calibration, or they would still continue to move forward but not on their hands and knees or through standard crawling. These segments in the trial were omitted from the analysis.

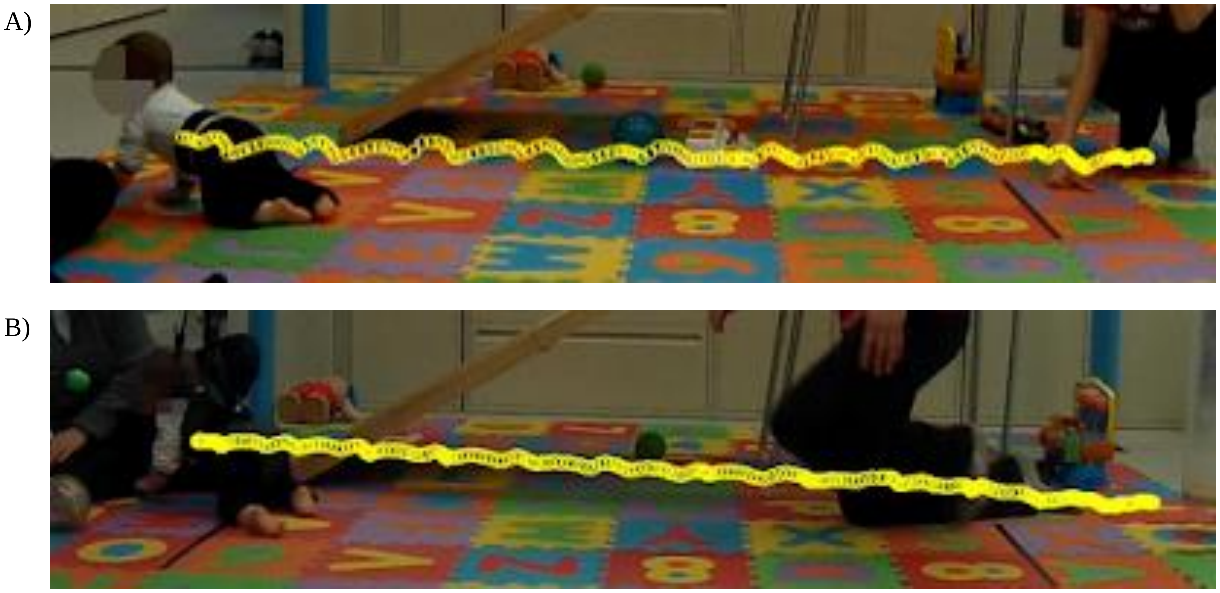

Figure 1. *Example of the C**o**M motion trajectories that were obtained during trials performed without (A) and with (B) the assistance from the BWS system.*

The data were inputted into MATLAB for further analyses. Prior to conducting numerical data and variable computations, the data had to be detrended allowing for the isolation of the crawling patterns to be separated from other extraneous movements of the body in space (e.g., moving towards a specific direction and not straight). Next, the following variables to quantify the motion of the CoM marker were computed: Total Distance, Lateral and Vertical Displacement, and Tortuosity Index. Total Distance is the length of the path from the onset to the offset of the crawling trial. The displacement is a vector quantity that refers to the overall change in the position of the CoM as it was oscillating. The vertical displacement specifically determines the amount the CoM marker moved up and down from the sagittal or side view, and the lateral displacement determines the amount the CoM marker moved from side to side from the dorsal or top view. Tortuosity Index is the ratio of the path length to the displacement between the two points.

RESULTS

In this preliminary investigation, a statistical approach (Wilcoxon Signed-rank test) was followed for the data from the TD group of infants, and an exploratory descriptive analysis approach was followed for the data of infants with DS. Data from both sessions were lumped as there was consistency in the data for all subjects for both days. Our graphs and image overlays revealed an oscillating path of the CoM marker motion throughout the trial for all infants. Overall, all infants' CoM motion paths were straighter when they crawled with the assistance from the BWS system. More specifically, for the group of TD infants, our results showed less vertical CoM marker displacement during crawling in the condition they used the BWS system compared to the condition prior (Pre vs. In; p = 0.028); however, CoM marker displacement was not significantly different between the two conditions that did not involve the assistance from the BWS system (Pre vs. Post; p = 0.173) (*Figure 2)*. Similarly, for the same group, a smaller tortuosity index was found in the condition infants used the BWS system compared to the condition prior (Pre vs. In; p = 0.028); this was again not significantly different between the two conditions that did not involve assistance from the BWS system (Pre vs. Post; p = 0.249).

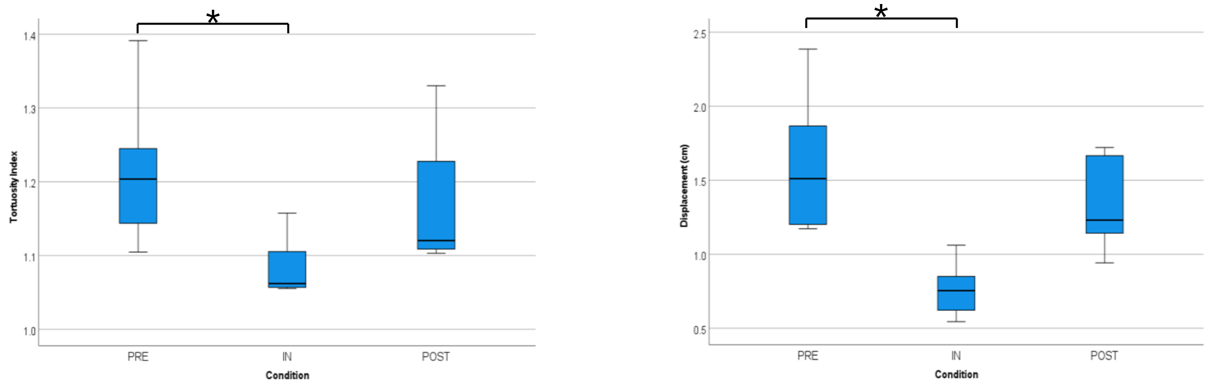

Figure 2. *Box plots depicting Tortuosity Index (Left) and Average Vertical Displacement (Right) of the C***o***M motion trajectory in the group of TD Infants.*

For the two infants with DS, vertical CoM marker displacement seems to also be less when infants are crawling with the assistance from the BWS system ($M_{In} = 0.84$, $SD_{In} = 0.14$) compared to the conditions before ($M_{Pre} = 1.14$, $SD_{Pre} = 0.30$) and after ($M_{Post} = 1.13$, $SD_{Post} = 0.01$). The same pattern seems to exist in the results from the tortuosity index, which shows a lower index when crawling with the assistance from the BWS system ($M_{In} = 1.03$, $SD_{In} = 0.006$) compared to before ($M_{Pre} = 1.08$, $SD_{Pre} = 0.004$) and after ($M_{Post} = 1.08$, $SD_{Post} = 0.02$) (*Figure 3)*.

Certain observations were also noted in the variability in the data between the two groups. Both infants with DS seem to present very similar patterns in their behavior (SDs reported above) whereas the data from the TD infants display greater dispersion in average vertical displacement ($SD_{Pre} = 0.46$, $SD_{In} = 0.18$, $SD_{Post} = 0.31$) and tortuosity index ($SD_{Pre} = 0.10$, $SD_{In} = 0.04$, $SD_{Post} = 0.09$). It is important to note, however, that this observation may also be due to the fact that the sample of TD infants is larger, so their data may be subject to more inter-subject variability. Nevertheless, the data from the infants with DS still suggest a pattern in the change of body movement across conditions similar to that of TD infants.

Overall, these pilot data suggest that infants' bodies moved in straighter paths toward the goal with the assistance from the BWS system, compared to without it. Lastly, it seems that both populations adapt to the BWS and show immediate changes in their body movement. Future investigations with larger sample sizes and formal statistical analyses will verify if this is true.

Figure 3. *Scatter plots depicting Tortuosity Index (Left) and Average Vertical Displacement (Right) of the C**o**M motion trajectory in the group of DS Infants.*

DISCUSSION

This examination provided pilot data on the immediate changes in infants' body movement while crawling through the use of a BWS system. Specifically, infants' bodies seem to move in straighter paths toward the end goal when they have the support from the BWS system, compared to without it. These changes were similar in both TD infants and infants with DS. It is worth to note that these effects refer to infants that had already acquired crawling on the hands and knees and may not be the same with infants that are at different stages of crawling development (e.g., belly crawling, etc.).

The aforementioned changes were quantified using variables computed from the position data of a marker placed on a specific location on the body as a proxy to the body's CoM. CoM motion is used in the study of movement biomechanics and can provide insight into how the body tries to minimize energy expenditure during locomotion. Locomotion at constant speed consists of cycles where both gravitational potential energy and kinetic energy of the CoM oscillate between maximum and minimum resulting in the CoM rising, falling, accelerating, and decelerating [81]. During crawling, infants' motion exhibited a cyclic pattern that could be explained by the inverted pendulum model. More specifically, and unlike bipedal walking in which a single inverted pendulum applies, quadrupeds appear to have more of a two-inverted pendulum; this can be imagined as one inverted pendulum right behind the other [82].

The two-inverted pendulum model, in comparison to the single one, may explain the different patterns in the vertical displacement and velocity of the body's CoM [82], [83], [84]. In contrast to bipedal walking, the maximum values of mechanical energy recovery are lower in quadrupedal locomotion, suggesting that energy exchange mechanisms during locomotion of quadrupeds may be different to that of bipeds [81], [85]–[88]. The infants' CoM during crawling seems to undergo two oscillations per stride, similar to the locomotion of other quadrupeds [82]. When infants move an arm with the contralateral leg, it would result in an oscillation; then, when they move the opposite arm with its respective contralateral leg, it would result in the second oscillation. The infants themselves may be more likely to choose a certain type of locomotion that would allow for a decrease in stress and metabolic power, and in this case the type of locomotion would be reflected in the way of movement of their CoM [15], [89].

The use of the BWS system during crawling seems to alter the aforementioned energy transfer mechanisms. This pilot investigation revealed a decrease in the vertical displacement and tortuosity index of the CoM during crawling while using BWS. The limbs’ push-off and landing events were more abrupt compared to the smooth events seen when infants were using the BWS system. It seems that the reduced load from the BWS system may result in less energy requirements from the infants to move their limbs and transfer their body forward. In addition, infants may not have to put in as much effort to control their balance while transitioning across the different cycles of crawling [76], [90]. As a result, requirements for activation of muscles responsible for generating forces towards maintaining balance and for propulsion may be less with the use of the BWS system [90]; which makes the use of this device useful to infants that have muscle weakness and other motor impairments.

To better understand the mechanisms of crawling locomotion in infants under the influence of BWS, future investigations can involve additional variables. Spatial and temporal parameters of gait can be examined through the quantification of limb falls during the gait cycle for the whole crawling trial [30]. For example, CoM displacement has been suggested to decrease if the limbs strike the ground at similarly spaced timed intervals [82]. Therefore, understanding the duration of the swing and stance phases can give insight on the crawling locomotion mechanisms. Another variable of interest is the velocity of the CoM, as previous research suggests that body weight unloading may result in a slower gait [91]; Lastly, as mentioned in the Methods section, for this investigation, data from subjects exhibiting army and belly crawling or other quadruped forms of locomotion (i.e., bear walking) were excluded from our analyses. Data collected while infants performed these different types of quadruped locomotion can be analyzed in the future to understand how the use of the BWS system may affect these types of activities as well.

The results from this investigation should be approached with caution as they came from a small sample. Future investigations with larger sample sizes and formal statistical analyses will verify our observations. Other limitations to this study are relevant to the data analyses. In our dataset, there were segments with missing data due to the marker being obscured by the moving beams of the BWS system. Further analyses can target some of these trials and through linear interpolation techniques (assuming the segments that are obscured are very small compared to the whole trial) more data can be considered in the dataset.

CONCLUSION

Crawling is a type of early locomotion that allows infants to explore their environment affecting other developmental systems. The current study assessed the effects of a BWS system use on the biomechanics of crawling in infants with and without DS. Pilot data from this investigation suggest that both populations adapt to the BWS immediately and show changes in their body movement. More specifically, infants from both groups move their bodies in straighter paths with the assistance from the BWS system, compared to without it. Future investigations with larger sample sizes and formal statistical analyses will examine if the latter is true.

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