Title
Exploring the Effects of Body Weight Support on Infant Crawling Gait

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Publication Date
2021-08-23

EXPLORING THE EFFECTS OF BODY WEIGHT SUPPORT ON INFANT CRAWLING GAIT

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A capstone project submitted for Graduation with University Honors

May 06, 2021

University Honors
University of California, Riverside

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ABSTRACT

According to the United Nations, there are roughly 130 million infants born each year. In addition, approximately one in six children in the US are diagnosed with a developmental disability (CDC, 2019). Because some of the developmental disabilities have negative effects on motor development, researchers have begun investigating how assistive technology can be used in combination with training to address infants' mobility impairments. This research report examines the immediate effects stemming from the use of an open-area body weight support device on infant crawling locomotion. More specifically, it discusses the rationale for addressing this research question and conducting this research study, and describes the study protocol and the data collection procedures. In addition, it provides information on the analysis tools developed for future use and presents preliminary results based on crawling data from one participant. Lastly, limitations and suggestions for further exploration of the data for this participant and for the whole group in the future are also discussed.

ACKNOWLEDGEMENTS

I would like to thank my faculty mentor, Dr. Elena Kokkoni, for her guidance and support in completing this capstone project. An extended gratitude for the members of Dr. Kokkoni's research group who also supported me, especially Dr. Amanda Arnold.

I would also like to thank the University Honors Program staff, especially Dr. Richard Cardullo and my honors counselor Mayra Jones, for their support and for giving me the opportunity to complete a capstone project.

Lastly, I would like to thank my parents, Joanne and Felix Solamo, my family, and friends for their continuous support during the completion this capstone project.

TABLE OF CONTENTS

INTRODUCTION

Infants' overall development is impacted by their ability for locomotion, which develops as infants discover how to move their bodies within the environment.[1,2] Crawling is a fundamental type of prone locomotion that emerges after upright sitting and before walking.[3] It is characterized by a sequential displacement of all four limbs, through a swing and stance phase, and with no stops or perturbations.[4–6] The swing phase is defined as the time that the limb is lifted off the surface of support, and the stance phase is the time that the limb is placed back on the surface of support.[4] Both the acquisition of crawling onset and crawling experience over time affect various aspects of an infant's development.

The ability to move around provides opportunities for visual motion processing, intercepting objects, and interacting with others, leading to the development of depth perception of the surroundings, spatial memory, and cognitive function.[1,7–9] For example, crawling infants who are tasked to move across the floor to a table and retrieve a toy have been found to be more successful than infants that are typically passively carried by their parents.[7] Additionally, crawling infants acquire unique experiences for visual guidance of their locomotion due to their closer view of the floor, which is not found in other types of locomotion such as walking.[8] Lastly, it seems that crawling experience is important for developing other motor skills later in life, such as the ability to perceive and imitate different body postures (aka motor imitation).[9] Consequently, understanding better the characteristics of crawling locomotion is essential so as to be able to design interventions and technology to promote crawling in populations that present impaired crawling ability and/or onset delays.

Infants learn by experience which is acquired while moving under different environmental and task conditions.[5,10] Typically developing (TD) infants move frequently, which strengthens the neural connections to a particular movement and increases stability in repeating various patterned actions over time.[11] Specifically in crawling, as infants practice this skill, they learn how to use opposite limbs and move those simultaneously.[4] Diagonal crawling gait is a more dynamically stable pattern, compared to the ipsilateral pattern, as it minimizes side to side variations of the center of mass.[12] Infants with Down syndrome (DS), however, do not seem to move as frequently and may move in different ways than their TD peers.[13] DS is a congenital disorder caused by an extra copy of chromosome 21 affecting about one in every 700 births.[14] Infants with DS face developmental delays, including in crawling skill acquisition.[14]

Many studies indicate that infants with DS acquire new skills and behaviors at a slower rate than their TD peers of the same age.[13,15] Although they present the same sequence of motor milestone development as TD infants, starting with sitting upright and crawling, as they progress to walking, the developmental gap between TD infants and infants with DS grows wider.[16–18] On average, infants with TD start hands-and-knees crawling by about 8-9 months,[4] while infants with DS start crawling by an average of about 15 months.[18] This discrepancy can be attributed to various changes in the infants' bodies as time progresses which can be related to the DS diagnosis, or simply, to growth. Bodily restrictions, such as joint hypermobility and muscle hypotonia can hinder movement and impact spatial development.[17] In addition, as infants get bigger, their center of gravity turns out to be higher and their base of support becomes smaller and less stable.[18] Consequently, infants with DS may need more time practicing movements in order to acquire and refine the crawling skill.[19]

A way to promote motor practice on skills not acquired yet, and hopefully decrease the developmental gap between TD infants and infants with DS, is through the use of assistive technology (AT). There are various forms of AT, ranging from low-technology equipment, such as switches, head pointers, picture boards, crutches, to more high-technology equipment, such as computers, and power wheelchairs.[20] A few examples of AT to promote mobility and locomotor ability specifically involve powered mobility devices, adapted canes, virtual reality technology, treadmills, and body weight support devices.[16,21–27] For example, a study focused on treadmill training of infants with DS provided opportunities for practicing a repeated pattern of stepping, resulting in a reduced delay in the onset of independent walking.[16] Another type of AT, more recently introduced for overground locomotor training, are body weight support (BWS) devices. These devices reduce the effect of gravitational force on the body that may hinder a user from performing movements on their untrained limbs. Nevertheless, reliance of the user on a BWS device to move can be avoided by reducing the amount of support as mobility improves.[22]

Previous studies have explored the effects of BWS on walking gait and general mobility in young children and infants with cerebral palsy,[28,29] spina bifida,[23] and DS.[24,25] In general, AT to assist various forms of locomotion early in life, such as crawling in infants and young children, is limited,[30,31] and to our knowledge, the effects of BWS on crawling gait of infants is not adequately explored. In addition, most of the studies on crawling focus primarily on TD infants,[4–7,32,33] and less on infants with DS.[17] By providing infants with DS with opportunities to practice crawling under altered conditions, such as by providing BWS, may lead to the acquisition of an earlier crawling onset compared to the average acquisition for infants with DS, the emergence of different styles of crawling (e.g., belly, hands-and-feet, hands-and-knees, etc.), and may improve their spatial awareness.

The goal of this research study is to assess changes in the crawling locomotion of infants with and without DS through the use of BWS. The BWS is provided through an open area support device that allows for the study of overground locomotion. The hypothesis is that immediate changes will be observed under BWS which will be transferred to crawling gait without BWS. Thus, this study focuses on the immediate differences of crawling gait characteristics across BWS conditions, and not the longitudinal effects of BWS on crawling.

METHODS

Data Sample

Restrictions placed on campus because of the COVID-19 pandemic did not allow for the analysis of the whole group of 15 participants. Therefore, this report focuses on the rationale for conducting this research study, and describes the study protocol and the data collection procedures. In addition, it provides information on the analysis tools developed for future use and presents preliminary results on the data from one participant. The participant is an 11-month-old TD infant with the acquired ability of hands and knees crawling without assistance.

Device

All infants used the assistance from an open area BWS device when crawling. The BWS device is an overhead canopy system that allows movement throughout the three-dimensional space. It consists of three 10-ft long beams; two stationary beams placed in parallel on opposite sides of the covered area, and one movable beam which is placed perpendicularly to the other beams. A harness is connected to the moveable beam that supports the user's body around the waist and through the crotch. More information on the setup and use of this specific BWS device type can be found in Kokkoni and Galloway (2019).[25]

Data Collection

All infants performed crawling trials under three conditions: without BWS, with BWS, and again without BWS. This protocol was followed in an effort to study transfer of learning across conditions, and to test whether potential new characteristics of crawling gait experienced in the second condition could be transferred into the third condition (and compare potential differences to the first condition). This is similar to an ABA research design that follows a series of baseline, treatment, and post-treatment periods, allowing for the study of learning of a new skill trained during the treatment period.[34]

Video recordings of each trial collected from a video action camera placed on the ceiling were utilized. The frame rate was set at 30 frames per second. A circular marker was placed in the middle of the lumbar region of the infants' body to analyze the movement of their body during crawling.

Data Analysis

In order to analyze the body movement of the TD infant during crawling gait across conditions, the crawling sequence had to be defined. Crawling onset and offset times were identified and annotated from the videos for each trial (*Figure 1*).

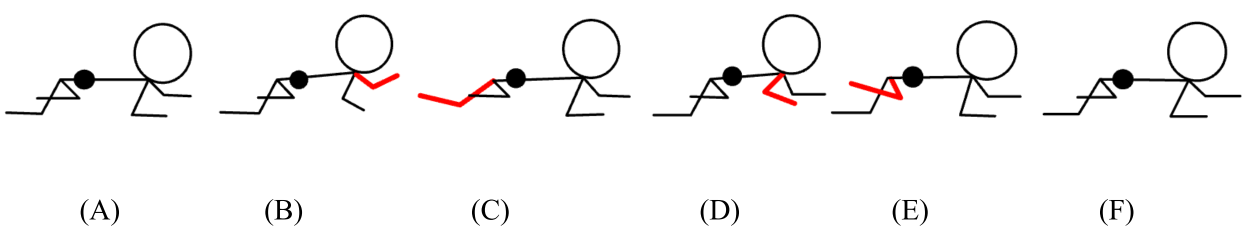
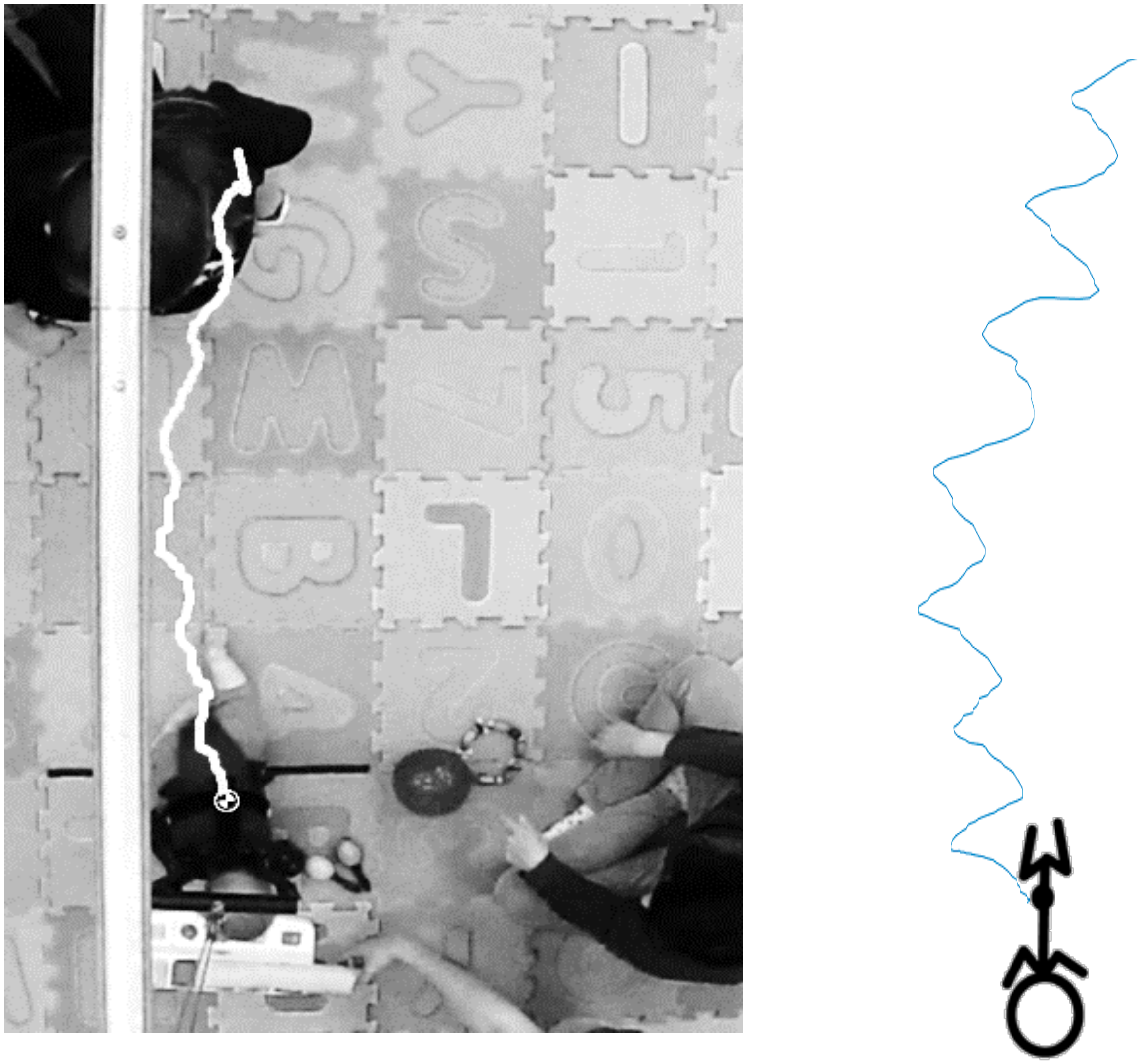


Figure 1. Illustration of one complete crawling cycle. The highlighted limb indicates motion. The marker on the lumbar region is also indicated. (A) Participant in starting hands and knees crawling position. (B) The first frame an arm is lifted indicating forward progression. (C) The opposite side knee is lifted. (D) The opposing arm is lifted. (E) The remaining knee is lifted. (F) All limbs have returned back to starting position.



(A) (B)

Figure 2. Examples of trajectories obtained from tracking the marker placed in the lumbar region. (A) Trajectory superimposed on the video. (B) Trajectory extracted and used for further analysis.

As shown in *Figure 1*, the onset of the crawling sequence was considered the first frame the participant started making a forward motion while being on their hands and knees and simultaneously lifting one of their hands off the ground (*Figure 1B*). The offset of the crawling sequence was considered the first frame that the last knee touched the ground at the end of each crawling cycle (*Figure 1E*).

The next step involved tracking of the circular marker placed on the infant's body in order to obtain the x and y coordinates at each frame. A video motion analysis software (Kinovea.org) was used to track the marker and obtain the movement trajectories (*Figure 2)*. The marker was tracked throughout the entirety of the trial, with the exception of when the infant did not display hands and knees crawling, the infant was held by another person, or the marker was occluded (*Figure 2*).

The analysis of the trajectories from every trial was performed in MATLAB (R2019b, The Mathworks Inc., MA) in order to compute the variables *Total Path*, *Average Velocity*, *Peak Velocity*, *Straightness Index*, and illustrate *Phase Portraits*.

The *Total Path* indicates the total distance travelled during the crawling trial. *Average Velocity* and *Peak Velocity* are mathematical calculations that provide information on the change of the distance travelled over time. The *Straightness Index* is the net displacement distance travelled, or the Euclidean distance between the start and final point, divided by the total length of the trajectory.[35] This is a unitless measurement of how straight the path is relative to the final point and varies from zero to one. The closer the path is to one the straighter the path. This index has also been used to study animal locomotion, in order to evaluate the animal's path tortuosity, the opposite of which (i.e., a straight path) is an indication of an animal's good orientation and searching behavior in their pursuit of a goal in space.[35]

Lastly, another variable considered to describe the obtained trajectories was the *Phase Portraits*. These phase plane portraits are movement geometric representations that provide information on the organization of the neuromuscular system during movement. They take note of stable and unstable states by the determination of attractors and repellers and are acquired by continuously plotting the displacement on the y axis against its instantaneous velocity on the x axis.[36] Such analysis has been previously used to study the movement of different body parts, such as the jaw movements in infant speech, leg movements in infant kicking, arm movements in infant reaching, and postural control in infant sitting.[36–38] In our context, this variable can provide information on the stability of the body movement during crawling in infants.

RESULTS

The preliminary results on the TD infant show support for our hypothesis. First, the infant successfully used the BWS and completed each trial by crawling from the beginning point to the ending point. However, there were times when the participant did not perform hands and knees crawling during the trial (e.g., paused to observe something in the environment). As mentioned previously, these were omitted from the computed variables.

The infant's performance in the initial condition, without the BWS, was as follows: *Average Velocity* = 12.87 cm/s, *Peak Velocity* = 15.37 cm/s, *Total Path* = 272.3 cm, and *Straightness Index* = 0.07076. After the use of BWS, in the third condition, the TD infant again did not use the BWS but displayed a slight increase in the following: *Average Velocity* = 13.29 cm/s, and S*traightness Index* = 0.07666, compared to the first condition. In addition, the following variables slightly decreased: *Total Path* = 260.7 cm, and *Peak Velocity* = 15.07 cm/s., compared to the first condition. This result suggests that the infant moved faster on average and in a straighter path toward the goal after the condition in which the infant crawled with BWS. Unfortunately, there was not enough usable data from the second condition with the participant utilizing the BWS, so analysis of the trajectory was omitted.

The next part of the analysis on the *Phase Portraits* required multiple steps. As it can also be observed in *Figure 2*, there is a trend associated with the direction of the infant, which is irrelevant to the movement of the trunk. Therefore, in order to perform the necessary calculations and accurately depict the phase portraits, these trends were removed in an initial step. *Figure 3* shows the original data and the detrended data, which were obtained from the analysis in MATLAB.

The next step was to utilize the detrended data in order to create the *Phase Portraits* that capture the behavior of a dynamical system by plotting the variable and its first derivative with respect to time. For this initial examination, and as also indicated by the yellow section of the detrended data lines, the *Phase Portraits* were computed utilizing portions of the data. Based on these sections, it seems that after the condition with the BWS, the infant presents more stable movement of the trunk during crawling.

DISCUSSION

The purpose of this research study was to explore the effects of BWS on the crawling gait of infants. The opportunity to practice overground crawling gait, through the use of an open area BWS device, may have beneficial effects on the crawling performance of infants with developmental delays, such as DS, and may provide opportunities for motor learning. Specifically, this report describes the rationale for addressing this research question, and details the study protocol and the data collection procedures. In addition, it provides information on the

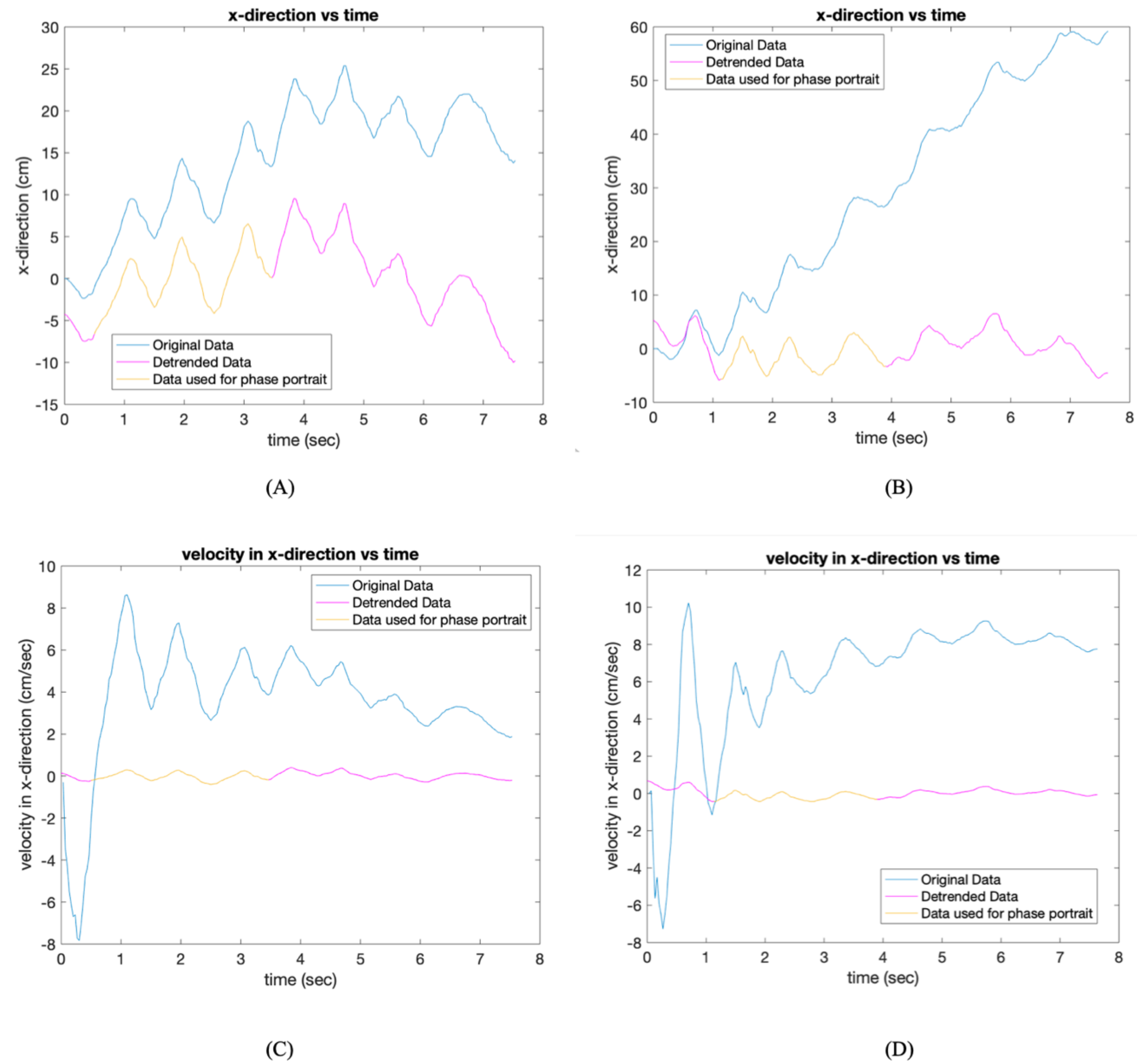
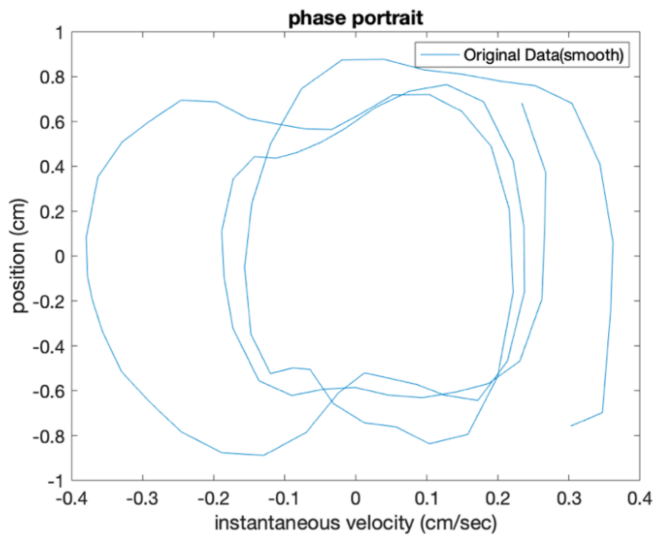
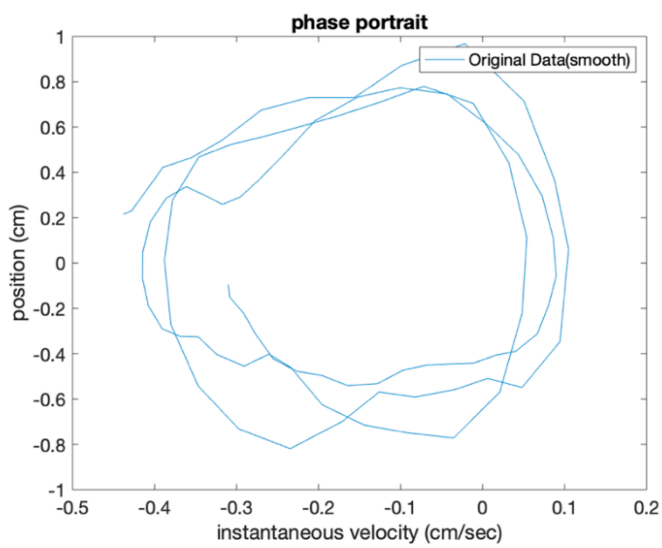


Figure 3. Graphs depicting the paths of the participant. Left: 1st condition, without BWS. Right:3rd condition, without BWS. (A) and (B): Position vs time graph in the x-direction. (C) and (D): Velocity vs time graph in the x direction. The blue lines include the trend from the change in direction of the infant, causing an increasing slope. The pink/yellow lines show the detrended to zero data. This process was done for the position vs. time and velocity vs time.



(A)



(B)

Figure 4. Phase portraits obtained by continuously plotting the displacement on the y axis against its instantaneous velocity on the x axis. (A) First condition, without the BWS. (B) Third condition, without BWS. The portrait in the bottom illustrates reduced variability on the oscillations of the marker over time.

analysis tools developed for future use and presents preliminary results on the data from a TD infant. During the crawling session, the objective for the infants was to crawl from a specified start toward an end point without restrictions to the amount of time needed to reach the goal. Preliminary results from one participant suggests that after BWS, crawling may become faster and more consistent and predictable compared to before the use of BWS. A group of variables was computed, such as different velocities, straightness index, path length, and phase portraits. Analysis of the remaining participants and formal statistical analysis in the future will define if this pilot result is confirmed. Nevertheless, the following paragraphs discuss the pilot results coming from that one participant infant.

Average and peak velocities were obtained from the participant data. Velocity can provide an insight on the changes of the swing and stance phases during crawling. Prior studies inferred that increasing speed comes mainly from the decrease in the stance phase while the swing phase remains constant.[12] Another study also suggests that superior limb coordination with a diagonal gait may produce a faster crawling speed resulting in higher performance, with the opposite being that low performers crawl at slower speeds, present longer crawling stride times, and poor limb coordination.[12] In our study, the TD infant's *Average Velocity* increased from 12.87 cm/s to 13.29 cm/s after the use of the BWS. However, the *Peak Velocity* decreased from 15.37 cm/s to 15.07 cm/s after BWS use. Although these findings are conflicting, the average velocity is the main indicator that the participant crawled faster after utilizing the BWS device.

Phase portraits showed oscillatory trends on body movement while performing crawling gait. Human infants are not the only animals that display quadruped locomotion behaviors.[6] The development is a result of improved posture, neuromuscular control, and experience, which is why it is vital for infants to utilize hands and knees crawling in an optimal way.[6] Due to the functionality of an infant during crawling gait, it is more mechanically constrained and not in an optimal form.[6] The oscillations indicate that the participant is moving towards the supporting leg, and swinging to the next leg for the next movement as defined through the swing and stance phase.[6] The period of oscillation shows that the infants have the same dynamic organization of movement and velocity as adult skilled movements.[39]

Phase portraits are used for gait analysis because of their cyclic, dynamic representations of motion shown by plotting position against velocity.[40] They have shown a pattern of increased gait stability through infant development, specifically for characterizing motion at a specific joint.[41] Since the participant was constantly moving during the trial, it is observed that the fluctuations in the radius of the phase portrait are consistent with the movement being made.[41] A study has shown that phase portraits for gait development may vary between children with a developmental coordination disorder and TD children.[40] Another study found that when an infant becomes a better walker, their trajectory shown on the phase portrait is more stable and has less variability, so that each orbit produces the same path.[42] This study is taking the concepts of improved walking through phase portrait analysis and applying it for crawling gait. Phase portraits can determine whether the participant has mastered crawling because the variability of the dynamics would cease.[42] Phase portrait analysis is used to understand the dynamics of movement of the participant and whether mastery of crawling has occurred.

Analyzing phase portraits is helpful for understanding the dynamics of crawling gait because portraits display elements of constant coordination.[39] By looking at different phase portraits, the participant in our study seems to have more consistent body motion during crawling in the third condition, after the BWS use. Consistency was determined by examining both phase portraits and analyzing the variability of the radius of each cyclic movement. Thus, a preliminary conclusion is that the BWS contributed to decreased swaying of the infant's body during crawling, as shown by the decreased radius of the phase portrait in the last condition without the BWS use. It seems that the BWS provided by the device through the overhead metal pole assists the infant with keeping the path of the body more stable.

The above discussion is based on the preliminary findings based on crawling data from one TD infant, and thus, there are some limitations and suggestions for further exploration of the data for this participant and for the whole group in the future. The major limitation to the completion of the analysis for this report was primarily due to the COVID-19 pandemic disrupting the analysis of crawling gait trials performed by more TD infants and infants with DS. Another limitation to the analysis of the data in this study is the various occlusions to the body marker, mainly stemming from the movable beam of the BWS device. Applying interpolation tools in the data may be useful in these cases as a future consideration.

Suggestions for future work also include considerations for more variables to describe the crawling gait and general future research directions. For example, a potential variable that could be computed is the duration of the swing and stance phases of each limb to further confirm whether the change in speed is due to the reduction of the stance phase duration. On another note, the specific analysis in this report is focused primarily on the hands and knees crawling style. This specific research study can be used as a reference for further work on AT that can be used as part of intervention to train other crawling gait styles, such as hands and feet crawling, belly crawling, or even walking. Lastly, based on previous findings on infant locomotion, it might also be beneficial to observe the number of falls or times the infants lose balance while crawling before and after using the BWS.[43]

CONCLUSION

Crawling is a motor developmental milestone that most infants acquire during the first few months of life. This timeline varies depending on various factors related to the environment, the organism, and the task itself, and is challenging for some populations, such as those diagnosed with DS. The present study examines the immediate effects of BWS on the crawling gait of infants and describes the use of various variables, such as velocities and phase portraits to assess changes in crawling. Future analysis will reveal the amount of change that BWS may have on the crawling gait of infants with and without DS.

REFERENCES

1. Campos JJ, Anderson DI, Barbu-Roth MA, Hubbard EM, Hertenstein MJ, Witherington D. Travel Broadens the Mind. *Infancy*. 2000;1(2):149-219. doi:https://doi.org/10.1207/S15327078IN0102_1

2. Adolph KE, Franchak JM. The development of motor behavior. *Wiley Interdisciplinary Reviews - Cognitive Sci*. 2017;8(1-2). doi:10.1002/wcs.1430

3. Adolph KE, Berger SE, Leo AJ. Developmental Continuity? Crawling, Cruising, and Walking. *Developmental Sci*. 2011;14(2):306-318. doi:10.1111/j.1467-7687.2010.00981.x

4. Freedland RL, Bertenthal BI. Developmental Changes in Interlimb Coordination: Transition to Hands-and-Knees Crawling. *Psychological Sci*. 1994;5(1):26-32.

5. Adolph KE, Vereijken B, Denny MA. Learning to Crawl. *Child Dev*. 1998;69(5):1299. doi:10.2307/1132267

6. Righetti L, Nylén A, Rosander K, Ijspeert AJ. Kinematic and Gait Similarities between Crawling Human Infants and Other Quadruped Mammals. *Front Neurol*. 2015;6. doi:10.3389/fneur.2015.00017

7. Clearfield MW. The role of crawling and walking experience in infant spatial memory. *Journal of Experimental Child Psychol*. 2004;89(3):214-241. doi:10.1016/j.jecp.2004.07.003

8. Kretch KS, Franchak JM, Adolph KE. Crawling and Walking Infants See the World Differently. *Child Dev*. 2014;85(4):1503-1518. doi:https://doi.org/10.1111/cdev.12206

9. McEwan MH, Dihoff RE, Brosvic GM. Early Infant Crawling Experience is Reflected in Later Motor Skill Development. *Perceptual and Motor Skills*. 1991;72(1):75-79. doi:10.2466/pms.1991.72.1.75

10. Kamm K, Thelen E, Jensen JL. A dynamical systems approach to motor development. *Physical Ther*. 1990;70(12):763-775. doi:10.1093/ptj/70.12.763

11. Hadders-Algra M. Early human motor development: From variation to the ability to vary and adapt. *Neuroscience and Biobehavioral Rev*. 2018;90:411-427. doi:10.1016/j.neubiorev.2018.05.009

12. Vitali RV, Cain SM, Davidson SP, Perkins NC. Human crawling performance and technique revealed by inertial measurement units. *Journal of Biomech*. 2019;84:121-128. doi:10.1016/j.jbiomech.2018.12.030

13. Ulrich BD, Ulrich DA. Spontaneous Leg Movements of Infants with down Syndrome and Nondisabled Infants. *Child Dev*. 1995;66(6):1844-1855. doi:10.2307/1131914

14. Selikowitz M. *Down Syndrome*. Oxford University Press; 2008.

15. Pueschel SM, Gallagher PL, Zartler AS, Pezzullo JC. Cognitive and learning processes in children with Down syndrome. *Research in Developmental Disabil*. 1987;8(1):21-37. doi:10.1016/0891-4222(87)90038-2

16. Ulrich DA, Ulrich BD, Angulo-Kinzler RM, Yun J. Treadmill Training of Infants With Down Syndrome: Evidence-Based Developmental Outcomes. *PEDIATRICS*. 2001;108(5):e84-e84. doi:10.1542/peds.108.5.e84

17. Santos GR dos, Cabral LC, Silva LR, et al. Physiotherapeutic stimulation in infants with Down syndrome to promote crawling. *Fisioterapia em Mov*. 2020;33. doi:10.1590/1980-5918.033.ao54

18. Palisano RJ, Walter SD, Russell DJ, et al. Gross motor function of children with down syndrome: Creation of motor growth curves. *Archives of Physical Medicine Rehabil*. 2001;82(4):494-500. doi:10.1053/apmr.2001.21956

19. de Campos AC, Rocha NACF, Savelsbergh GJP. Development of reaching and grasping skills in infants with Down syndrome. *Research in Developmental Disabil*. 2010;31(1):70-80. doi:10.1016/j.ridd.2009.07.015

20. Dugan LM, Campbell PH, Wilcox MJ. Making Decisions About Assistive Technology With Infants and Toddlers. *Top Early Child Special Educ*. 2006;26(1):25-32. doi:10.1177/02711214060260010301

21. Cuturi LF, Aggius-Vella E, Campus C, Parmiggiani A, Gori M. From science to technology: Orientation and mobility in blind children and adults. *Neuroscience and Biobehavioral Rev*. 2016;71:240-251. doi:10.1016/j.neubiorev.2016.08.019

22. Frey M, Colombo G, Vaglio M, Bucher R, Jorg M, Riener R. A Novel Mechatronic Body Weight Support System. *IEEE Transactions on Neural Systems Rehabilitation Eng*. 2006;14(3):311-321. doi:10.1109/TNSRE.2006.881556

23. Kokkoni E, Logan SW, Stoner T, Peffley T, Galloway JC. Use of an In-Home Body Weight Support System by a Child With Spina Bifida. *Pediatric Physical Ther*apy 2018;30(3):E1. doi:10.1097/PEP.0000000000000516

24. Kokkoni E, Stoner T, Galloway JC. In-Home Mobility Training With a Portable Body Weight Support System of an Infant With Down Syndrome. *Pediatric Physical Therapy* 2020;32(4):E76-E82. doi:10.1097/PEP.0000000000000752

25. Kokkoni E, Galloway JC. User-centred assistive technology assessment of a portable open-area body weight support system for in-home use. *Disability and Rehabilitation: Assistive Technol*. Published online December 6, 2019:1-8. doi:10.1080/17483107.2019.1683236

26. Feldner HA, Logan SW, Galloway JC. Why the time is right for a radical paradigm shift in early powered mobility: the role of powered mobility technology devices, policy and stakeholders. *Disability and Rehabilitation: Assistive Technol*. 2016;11(2):89-102. doi:10.3109/17483107.2015.1079651

27. Wuang Y-P, Chiang C-S, Su C-Y, Wang C-C. Effectiveness of virtual reality using Wii gaming technology in children with Down syndrome. *Research in Developmental Disabil*. 2011;32(1):312-321. doi:10.1016/j.ridd.2010.10.002

28. PROSSER LA, OHLRICH LB, CURATALO LA, ALTER KE, DAMIANO DL. Feasibility and preliminary effectiveness of a novel mobility training intervention in infants and toddlers with cerebral palsy. *Developmental Neurorehabilitation*. 2012;15(4):259-266. doi:10.3109/17518423.2012.687782

29. Pierce SR, Skorup J, Alcott M, Bochnak M, Paremski AC, Prosser LA. The Use of Dynamic Weight Support with Principles of Infant Learning in a Child with Cerebral Palsy: A Case Report. *Physical and Occupational Therapy in Pediatr*. 2021;41(2):166-175. doi:10.1080/01942638.2020.1766638

30. Arnold A, Haworth J, Moran V, Abulhasan A, Steinbuch N, Kokkoni E. Exploring the Unmet Need for Technology to Promote Motor Ability in Children Under 5 Years of Age: A Systematic Review. *Archives of Rehabilitation Research and Clinical Transl*. 2020;2:100051. doi:10.1016/j.arrct.2020.100051

31. Ghazi MA, Nash MD, Fagg AH, Ding L, Kolobe THA, Miller DP. Novel Assistive Device for Teaching Crawling Skills to Infants. In: Wettergreen DS, Barfoot TD, eds. *Field and Service Robotics*. Vol 113. Springer Tracts in Advanced Robotics. Springer International Publishing; 2016:593-605. doi:10.1007/978-3-319-27702-8_39

32. Patrick SK, Noah JA, Yang JF. Developmental constraints of quadrupedal coordination across crawling styles in human infants. *Journal of Neurophysiol*. 2012;107(11):3050-3061. doi:10.1152/jn.00029.2012

33. Patrick SK, Noah JA, Yang JF. Interlimb Coordination in Human Crawling Reveals Similarities in Development and Neural Control With Quadrupeds. *Journal of Neurophysiol*. 2009;101(2):603-613. doi:10.1152/jn.91125.2008

34. Chiang I-CA, Jhangiani RS, Price PC. Single-Subject Research Designs. In: *Research Methods in Psychology*. BCcampus; 2015. Accessed November 24, 2020. https://opentextbc.ca/researchmethods/chapter/single-subject-research-designs/

35. Benhamou S. How to reliably estimate the tortuosity of an animal's path: straightness, sinuosity, or fractal dimension? *Journal of Theoretical Biol*. 2004;229(2):209-220. doi:10.1016/j.jtbi.2004.03.016

36. Thelen E, Corbetta D, Kamm K, Spencer JP, Schneider K, Zernicke RF. The Transition to Reaching: Mapping Intention and Intrinsic Dynamics. *Child Dev*. 1993;64(4):1058-1098. doi:https://doi.org/10.1111/j.1467-8624.1993.tb04188.x

37. Kyvelidou A, Stuberg WA, Harbourne RT, Deffeyes JE, Blanke D, Stergiou N. Development of upper body coordination during sitting in typically developing infants. *Pediatric Res*. 2009;65(5):553-558. doi:10.1203/PDR.0b013e31819d9051

38. Kelso JAS, Vatikiotis-Bateson E, Saltzman EL, Kay B. A qualitative dynamic analysis of reiterant speech production: Phase portraits, kinematics, and dynamic modeling. *Journal of the Acoustical Society of Am*. 1985;77(1):266-280. doi:10.1121/1.392268

39. Thelen E, Kelso JAS, Fogel A. Self-organizing Systems and Infant Motor Development. *Developmental Rev*. 1987;(7):39-65.

40. DiBerardino LA, Polk JD, Rosengren KS, Spencer-Smith JB, Hsiao-Wecksler ET. Quantifying complexity and variability in phase portraits of gait. *Clinical Biomech*. 2010;25(6):552-556. doi:10.1016/j.clinbiomech.2010.03.007

41. Polk JD, Spencer-Smith J, DiBerardino L, Ellis D, Downen M, Rosengren KS. Quantifying variability in phase portraits: Application to gait ontogeny. *Infant Behavior and Dev*. 2008;31(2):302-306. doi:10.1016/j.infbeh.2007.10.005

42. Piek JP. The role of variability in early motor development. *Infant Behavior and Dev*. 2002;25(4):452-465. doi:10.1016/S0163-6383(02)00145-5

43. Adolph KE, Cole WG, Komati M, et al. How Do You Learn to Walk? Thousands of Steps and Dozens of Falls per Day. *Psychological Sci*. 2012;23(11):1387-1394. doi:10.1177/0956797612446346