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ORIGINAL RESEARCH

Gait Initiation of New Walkers and the Adult's Role in Regulating Directionality of the Child's Body Motion

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This study examines how adults apply forces to regulate new walkers' body sway directions while assisting them in standing and initiating their first steps. Eight healthy, typically developing young children who could stand independently and walk a few steps with an adult's support participated in this study and were included for data analyses. Adults wore instrumented force gloves and placed their hands on their child's hips to assist them in standing, then released glove contact with their child to allow their child to initiate walking. Using the glove force profiles, three phases (Stabilization, Relaxation, and Initiation) of adults' support were determined. Results showed that adults gradually reduced their assistance in both the antero-posterior (AP) and mediolateral (ML) directions, before releasing their hands. They also influenced the directionality of their child's center of mass (CoM) so that it was in the AP rather than ML direction. Furthermore, the behavior of the child's CoM in the ML direction during the Initiation Phase was related to the latency with which the child initiated the first step. These findings support the view that adults play a role in modulating the directionality of the child's body motion by transforming body sway into gait initiation.

Keywords: children, kinematics, motion analysis, motor performance

Children taking their first steps are usually assisted by an adult providing postural support. Such support may typically be thought of as keeping the child from falling. However, the opportunity for the child to actively explore the forces acting on the body during standing body sway may be an important part of learning

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to initiate gait and walk (Brenière & Bril, 1998; Bril, Dupuy, Dietrich, & Corbetta, 2015; Joh & Adolph, 2006; Kubo & Ulrich, 2006). Thus, an additional and crucial role of the adult may be to provide a safe environment for learning: the adult may assist the child's learning by selectively stabilizing some forces acting on the body, while allowing instability of other forces to persist. In particular, adults may damp out or stabilize mediolateral (ML) oscillations, but not antero-posterior (AP) oscillations, in anticipation of the inherent ML and AP characteristics of the gait cycle (Bauby & Kuo, 2000; O'Connor & Kuo, 2009). In this way, the adult may not only regulate the degrees of freedom of oscillation of the child's body center of mass (CoM) and center of pressure (CoP), but may also promote gait initiation by allowing the child to transform the AP body sway into forward stepping (Bril et al., 2015). We were particularly interested in this process, because we are developing assistive robotic devices which emulate the role of the adult in promoting gait initiation and walking in developmentally delayed children (Park et al., 2017). A goal of this study, therefore, was to examine how adults may selectively regulate the directionality of the body sway motion while new walkers are standing and taking their first steps.

To examine the role of the adult in using selective application of forces to regulate directionality of the behavior of the child's CoM, we custom fabricated a pair of gloves with embedded six-axis force/torque sensors. During tests in a motion capture laboratory setting, these were worn by adults and placed on the hips of their newly walking toddlers as each child stood on a force platform. The contact of the gloves with the child's hips was then released to allow the child to initiate walking. At the same time, body marker motion was captured by a Vicon motion capture system (see, e.g., Hsu, Miranda, Chistolini, & Goldfield, 2016), so that we were able to simultaneously measure forces applied to the child's hips by the adult, force platform data, and kinematics during standing and of the first steps of each child. We chose to measure forces applied at the hips because, at least during adult walking, hip proprioceptive information influences control of ML stability (Roden-Reynolds, Walker, Wasserman, & Dean, 2015). Moreover, the design of our assistive robotic devices for children includes a subsystem component which regulates ML and AP sway through cable attachments to a garment worn at the hips (Park et al., 2017). By measuring the actual forces employed during adult assistance, as well as CoM and kinematic parameters of the child's body motion during standing and walking, we were able to guide the design of our assistive pediatric robotic devices.

We hypothesized that adult regulation of the child's learning to walk would be a dynamic process which depended upon the child's behavior, and not simply a static application of force at the hips. To test this hypothesis, we identified a "stabilization phase", in which the adult assisted the child in standing on a force platform. During this initial phase of adult regulation, we expected the forces applied with the gloves to be directed at the hips in order to stabilize the standing child's ML sway, but be modulated according to the behavior of the child's CoM. Additionally, we identified a "relaxation phase," in which the adult reduced glove assistance in order to allow the child to stand independently, and then initiate walking. We were interested in determining the dynamic force modulation of the gloves by the adult (a) as the child was being stabilized, and (b) as the child prepared to initiate their first step by shifting the CoM in AP and ML directions.

Lastly, we identified an "initiation phase," in which the adult released the hands from contact with the child's hips to first toe off. In this subsequent phase, we examined the relation between the child's CoM behavior and the amount of time the child stood independently before the initiation of the first step. We used this data to determine if some, or all of the children, were able to independently leverage the forces acting on the body to promote an initial step. In summary, the process of the adult regulation of the child's learning to walk were divided into three phases, where the first two, stabilization and release phases, were under the control of the adult, while the third one, the initiation phase, was under the control of the child.

Methods

Participants

Fifteen healthy, typically developing young children who could stand independently and take a few independent steps to a support surface (e.g., furniture or wall) at home, were recruited for this study. Each child participated in one visit after the parent provided a written informed consent. Among these 15 recruited participants, four could not stand independently, three could not initiate walking, and eight were able to stand independently and walk during the visit. Therefore, only those who could stand independently and walk during the visit were included for data analyses. The characteristics of these eight participants (two boys, six girls, mean age: 12.7 months) who were included for data analyses are shown in Table 1. All experimental procedures and recruitment materials used for this study were approved by Harvard Medical School and Boston Children's Hospital Institutional Review Boards.

Instrumented Gloves

To measure the interactive forces applied by the adult to the child's torso, we designed a pair of instrumented gloves for the adult to wear while holding the child

Table 1 Participant Characteristics

Participant	Sex	Age (months)	Parent-reported Walking Ability	Usable Trials
S1	Female	14	Able to walk 1–3 steps	2
S2	Female	12	Able to walk a few steps	2
S3	Male	10	Able to walk a few steps	2
S4	Female	13	Able to walk 2–3 steps	5
S5	Female	15.5	Able to walk a few steps	2
S6	Male	13	Able to walk a few steps	7
S7	Female	10	Able to walk a few steps	4
S8	Female	14	Able to walk a few steps	3

in a standing posture (Figure 1). Each glove consisted of two 3D-printed interfaces which sandwich a six-axis force/torque sensor (Mini40, ATI Industrial Automation, Apex, NC). One interface consisted of a curved surface designed to conform to the child's torso at the hip as the adult holds the child. To improve the comfort of the glove for the child, the interface was covered with a sleeve molded from low-durometer silicone rubber (Ecoflex 30, Smooth-On, Inc., Macungie, PA). The sleeve was removable for cleaning after each study visit. The other interface was an oval-shaped dome designed to fit into the adult's cupped palm, with straps used to secure the plate to the hand. A rigid acrylic plate with attached retroreflective motion capture markers extended from the bottom face of the dome. The placement of this marker plate allowed for motion-capture tracking of the glove position and orientation without being occluded by the child's arms.

When the adult wore the gloves, and held the child in each trial, the force sensors were located in the middle of the adult's hands and child's torso so that the sensor X, Y, and Z coordinates were in line with the child's torso ML, AP, and vertical directions. These instrumented gloves could measure the shear force up to 44.5 N and the compression force up to 133.4 N with a resolution of 0.01 N and 0.02 N, respectively.

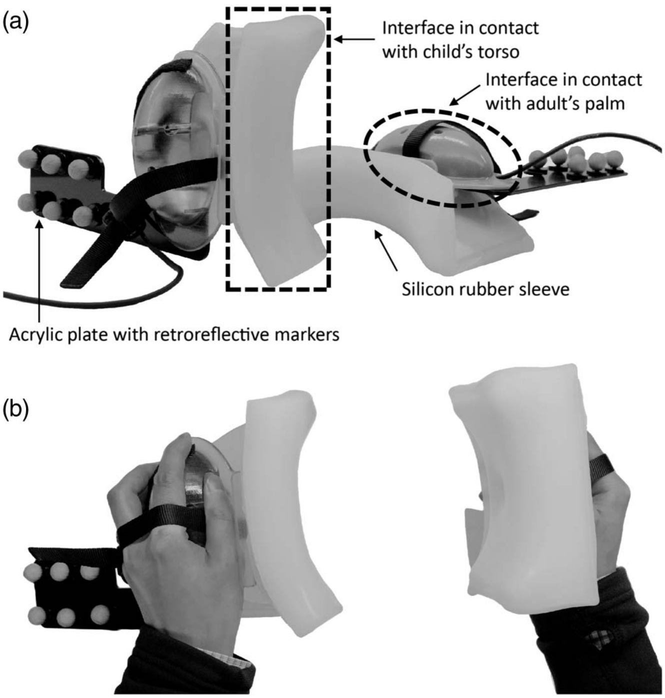

Figure 1 — The sensor-laden instrumented gloves. (a) The components of the gloves. A six-axis force/torque sensor is sandwiched between the two interfaces. (b) The illustration of the gloves worn by the adult.

Procedures

For motion capture, retroreflective surface markers were placed on the instrumented gloves and each participant's head, trunk, pelvis, upper arms, forearms, thighs, shanks, and feet (Figure 2). The cameras of a hybrid Vicon (Centennial, CO) MX T-Series and Bonita motion capture system surrounded two force platforms (AMTI, Watertown, MA) located in the center of the lab. The total length of the two platforms was approximately 1 m. The instrumented gloves and the force platforms were wired to, and synchronized with, the motion capture system. The position of the retroreflective markers data was sampled at 120 Hz. The ground reaction forces and glove forces were sampled at 1200 Hz.

Two adults assisted in the testing. The parent was instructed to stand next to but not in contact with any of the force platforms, wear the instrumented gloves and assist their child in standing barefoot on the closest force platform. After the child was stabilized, the parent released their hands from the child's hips, allowing their child to initiate walking. The other parent, or one of the researchers, sat at the end of the other force platform to encourage the participant to walk forward. Successful walking trials, in which the participant walked from one force platform to the other without falling (about 4–6 steps), were recorded for further analysis.

Data Processing and Analyses

The retroreflective marker data were labeled using Vicon Nexus 1.8.5 software (Centennial, CO) and then processed using Visual3D v5 software (C-Motion,

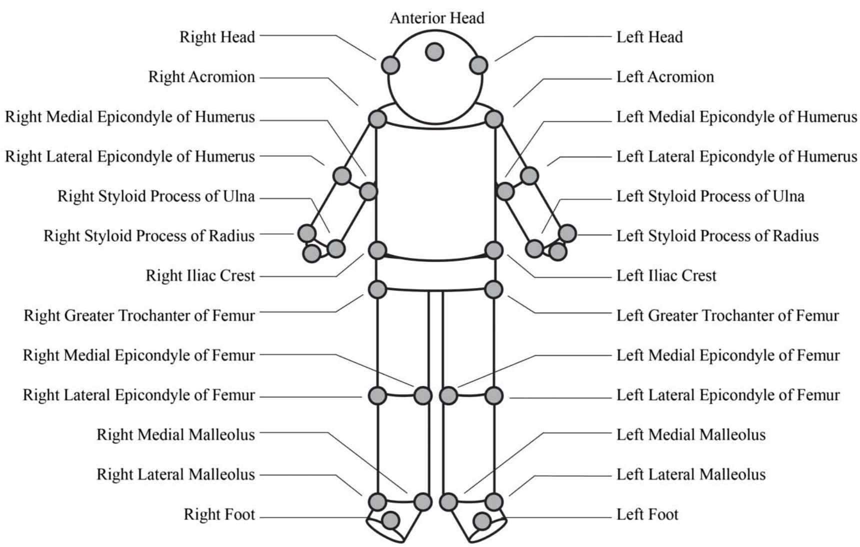

Figure 2 — The illustration of the marker placement on the 15-segment model. The retroreflective markers were placed on the body landmarks of the head, torso, pelvis, upper arms, lower arms, thighs, shanks, and feet.

Germantown, MD). Kinematic data were filtered using a 4th-order low-pass Butterworth filter with a cutoff frequency of 6 Hz. A 12-segment kinematic model (Figure 2) with its center of mass (i.e., the whole body CoM) location was built for each participant using Schneider and Zernicke's (1992) anthropometric estimates of the body segment masses and inertial properties. The gait events of initiation, heel strike, and toe off for the left and right strides were determined using algorithms proposed by Hreljac and Marshall (2000). The heel strike was defined when the peak vertical acceleration of the heel occurred. Here, we used the midpoint of the lateral and medial malleolus markers to represent the heel. The toe off was defined as the peak horizontal acceleration of the foot marker. The events of hands on (On) and hands release (Off) were identified as the compressive force exceeded or fell below 0 N, respectively.

When the parent assisted their child in standing on a force platform, two distinct compressive force profiles were observed (Figure 3). At first, larger compressive forces were generated by the parent. Later, the compressive forces from the parent were reduced. These two force profiles were distinguished by a "relax" event (Relax), in which the local minimum of the first derivative of the force occurred. Using these events, the Stabilization Phase, Relaxation Phase, and Initiation Phase were defined as the period between On and Relax, Relax and Off, and Off and the initiation of the first step. To calculate kinematics and kinetics, three-dimensional glove forces and CoM trajectory of the child were expressed in the lab coordinate system. The average absolute glove force from the right and left gloves was then calculated to represent the average assistive force the parents provided. The glove mean forces, CoM range, the phase duration during the Stabilization, Relaxation, and/or Initiation Phases (Table 2) of each of the collected successful trials (see Table 1 for the number of the successful trials of each participant) were first analyzed. The mean of these average variables of the trials per participant were then calculated to represent the performance of each individual. Together, these variables allowed us to measure the adult-child interactive forces, as well as the child's body sway while standing and the child's gait initiation. A computed ratio between the CoM range in the ML and AP directions allowed us to measure the direction in which the CoM movement was more dominant. For example, a ratio greater than 1 indicated that the range of CoM in the ML direction was larger than in the AP direction, indicating a more frontal than sagittal plane movement.

Statistical Analyses

Statistical analyses were performed using GraphPad Prism 7 (GraphPad Software, La Jolla. CA). Due to the small sample size, nonparametric Wilcoxon signed-rank tests were applied to compare the effect of phase (Stabilization Phase vs. Relaxation Phase) on the mean glove force, the range of CoM in the AP and ML directions, and the ratio of the range of the CoM. These variables were compared pairwise within each participant, allowing us to examine participants as their own controls. Statistical significance was set at an alpha level of 0.05. Additionally, the effect size was calculated to quantify the difference between phases for the outcome variables. An effect size of 0.2 is considered a small effect, 0.5 is considered a medium effect, and 0.8 is considered a large effect (Portney & Watkins, 2009).

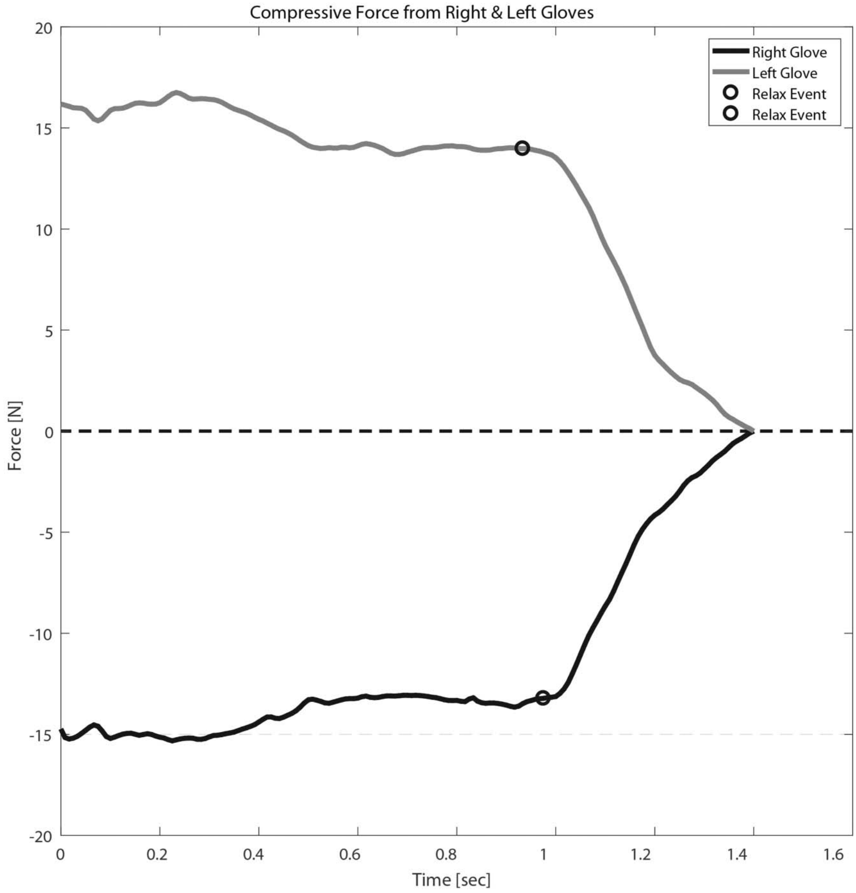

Figure 3 — The example trial of the right and left compressive forces applied from the adult to a participant. Circles denote the occurrences of the relax events.

A Pearson correlation coefficient (r) was used to measure the relation between the initiation time and the CoM range in AP or ML direction. We used this approach to determine the relation between the child's body motion and gait initiation. In general, $r < 0.25$ indicates little relationship between two variables; $0.25 < r < 0.50$ indicates a fair relationship; $0.50 < r < 0.75$ indicates a moderate to good relationship; and $r > 0.75$ indicates a good to strong relationship (Portney & Watkins, 2009). Furthermore, linear regression was performed to assess whether the initiation time could be predicted by the CoM range in the AP or ML direction.

Results

The results of this study are presented in two parts: (a) outcome variables of the group data to show general trends, and (b) outcome variables of individuals to show individual differences and variability in ways that the participants leveraged forces acting on their body.

Group Data

During the period that the adult released the gloves from the child's torso (i.e., the Relaxation Phase), the glove AP force of each subject was, on average, 23% lower ($p = .04$) than during the Stabilization Phase, in which the adult assisted the children in standing (see Table 3). Additionally, the glove ML force of each subject during the Relaxation Phase was, on average, 58% lower ($p < .01$) than during the Stabilization Phase. These findings suggest that adults reduced their assistance in both the AP and ML directions to allow the child to stand independently, and then to initiate walking, before releasing their hands from the child's hips.

Table 2 The Description of the Outcome Variables

Outcome Variable	Description
During Stabilization/Relaxation Phase	
Glove Mean in AP	The average glove force (N) in the anterior-posterior (AP) direction
Glove Mean in ML	The average glove force (N) in the mediolateral (ML) direction
CoM Range in AP[a]	The range (m) of CoM trajectory in the AP direction
CoM Range in ML[a]	The range (m) of CoM trajectory in the ML direction
CoM Range Ratio	The ratio (ML/AP) of CoM range in ML to CoM range in AP
Phase Duration	
Stabilization Time	The time (s) between On and Relax events
Relaxation Time	The time (s) between Relax and Off events
Initiation Time	The time (s) between Off event and child's first step initiation

[a]Range is defined as the value between the maximum and the minimum of the CoM in AP or ML. CoM = center of mass.

Table 3 Mean (*SD*) and the Results of the Wilcoxon Signed-Ranks Test on the Phase Difference of the Outcome Variables

	Phase			
Outcome Variable	Stabilization	Relaxation	*p*-value	Effect Size
Glove Mean in AP	2.71 (1.34)	2.02 (1.19)	**.04**	0.53
Glove Mean in ML	11.47 (7.24)	5.18 (4.33)	**<.01**	0.63
CoM Range in AP	0.016 (0.004)	0.020 (0.018)	.74	–0.11
CoM Range in ML	0.022 (0.013)	0.018 (0.018)	.20	0.35
CoM Range Ratio	1.35 (0.71)	0.87 (0.42)	**.02**	0.56

Note. Statistical significances ($p < .05$) are highlighted in bold. AP = antero-posterior; ML = mediolateral.

While the adult reduced assistive forces in both the AP and ML directions, no difference between phases was found in the range of CoM movement in either the AP or ML direction (Table 3). This finding suggests that the range of the child's CoM movement was not limited by the modulation of the assistance from the adult. However, the analyses on the relative motion between the ML and AP direction revealed that there was a significant difference between phases ($p = .02$) in the ratio of the range of CoM movement (Table 3). When taking the range of the CoM movement in the AP direction as the reference, the range of the CoM movement in the ML direction was relatively higher during the Stabilization Phase than it was during the Relaxation Phase (1.35 vs. 0.87). This finding indicates that the CoM movement changed from moving more in the ML direction (CoM range ML/AP ratio > 1) during the Stabilization Phase to moving more in the AP direction (ratio < 1) during the Relaxation Phase. Taken together, these results indicate that despite adults reducing their assistive forces, they still modulated the directionality of the child's body motion.

After the adult released their support, there was a good to strong relationship ($r = 0.92$, $p < .01$) between the initiation time and the CoM range in the ML during Initiation Phase (Table 4). The linear regression of these two variables with individual results are shown in Figure 4. The slope of this regression line is 35.1 sec/m and the goodness of fit (R^2) is 0.84. In general, participants who initiated their first step sooner demonstrated a smaller range of CoM movement during the Initiation Phase. Those who stood independently longer in the Initiation Phase showed a higher range of CoM movement before they initiated walking.

Individual Data

To more closely examine the differences between the participants, individual results are presented in Figure 5. Furthermore, results from our participants were visually distributed in two groups: S1, S3, S5, S6, and S8 as one group, in which participants initiated their walking faster while showing lower range of CoM movement; and S2, S4, and S7 as the other group, in which children stood longer before taking their first step while demonstrating larger range of CoM movement. Therefore, individual results were also divided into two groups.

In the group of those who walked sooner with a lower range of CoM movement during Initiation Phase, the average initiation time was 0.42 second, and the average CoM range in the ML during Initiation Phase was 0.01 m. Before adults released their support, the average durations of the Stabilization Phase and

Table 4 The Correlation Coefficient (*r*) and *p*-value of the Correlation Between Initiation Time and Center of Mass (CoM) in Antero-Posterior (AP)/Mediolateral (ML) During Initiation Phase

Correlation	Initiation Time
CoM Range in AP during Initiation Phase	$r = 0.38$, $p = .35$
CoM Range in ML during Initiation Phase	$r = 0.92$, $p <$ **.01**

Note. Statistical significance ($p < .05$) is highlighted in bold. CoM = center of mass; AP = antero-posterior; ML = mediolateral.

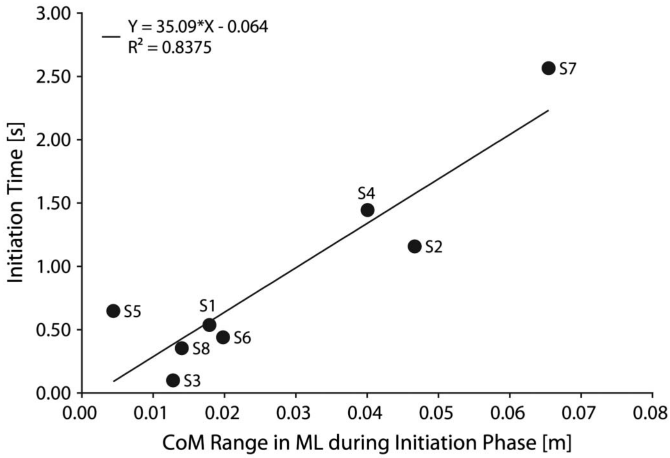

Figure 4 — The equation and goodness of fit (R^2) of the linear regression of the initiation time and center of mass range in mediolateral during the Initiation Phase with individual results.

Relaxation Phase were 1.53 seconds and 0.48 seconds, respectively. Furthermore, the average forces generated by the parent were 15.4 N during the Stabilization Phase and 7.4 N during the Relaxation Phase. By contrast, in the other group, the average initiation time was 1.72 seconds, and the average CoM range in the ML during Initiation Phase was 0.05 m. Children were supported by adults for, on average, 1.16 seconds during the Stabilization Phase and 0.39 seconds during the Relaxation Phase. Lastly, the average assistive forces during the Stabilization Phase and Relaxation Phase were 4.9 N and 1.5 N, respectively. The individual results demonstrate the differences and variability of how the adult assisted the child in standing and gait initiation and how the child responded to the support acted on their body.

In summary, distinct force patterns were observed in both the AP and ML directions when the adult assisted the child in standing and walking. During the Stabilization Phase, the CoM movement of the child was, on average, 1.35 times higher in the ML direction, when compared to the movement in the AP direction. During the Relaxation Phase, the child had already been stabilized in the ML direction, even without receiving much ML support from the parent. This may have allowed the child greater freedom to move in the AP direction, thus more readily initiating gait. After the Relaxation Phase, the child's CoM range in the ML during Initiation Phase was highly correlated with the initiation time. Participants who demonstrated a higher range of CoM movement in the ML direction initiated their walking more slowly than those who showed a smaller range of CoM movement.

Discussion

This study is among the first to examine how the adult may assist the child by modulating the forces applied to the child's body during standing and gait

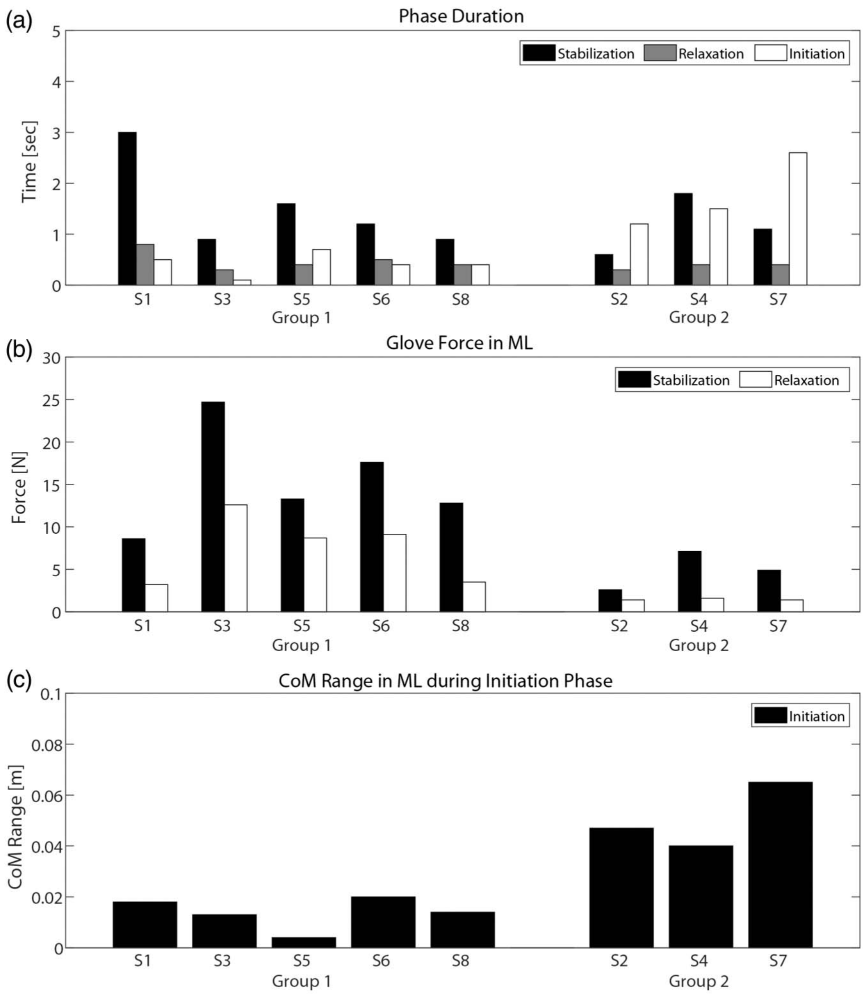

Figure 5 — The individual results. (a) The average phase duration of the Stabilization, Relaxation, and Initiation Phases. (b) The mediolateral (ML) glove force during the Stabilization and Relaxation Phases. (c) The center of mass range in ML during the Initiation Phase.

initiation. Our hypothesis was that assistance from the adult would be a dynamic process, which depended on the child's behavior. By examining the force profiles from the gloves relative to the force platform data, we were able to begin to get a picture of how the adult may assist their newly walking child in learning to manage the forces acting on the body. Overall, we observed two force profiles generated by glove output while the adult held the child at the hips. Initially, in the Stabilization Phase, the adult provided larger forces to support the child in both the AP and the ML directions. Later, the adult reduced the assistive forces in both directions in the

Relaxation Phase. While the adult's assistive forces were reduced, there was no effect on the range of the child's CoM movement between phases, suggesting that the child has been stabilized so the adult could reduce the assistance without affecting the behavior of the child's CoM. Meanwhile, the ratio of the range of CoM movement changed from moving more in the ML direction during Stabilization Phase to moving more in the AP direction during Relaxation Phase. These findings suggest that while adults might not necessarily restrict the child's CoM movement in either direction, they transform their child's body sway direction, allowing their child to explore the forces acting on the body. In this way, the adult may not necessarily limit the degrees of freedom of oscillation of the child's CoM but may promote gait initiation by allowing the child to transform body sway into forward stepping, as the exploration of AP and ML coupling is important in the early stage of independent walking (Kubo & Ulrich, 2006).

After adults removed their manual support, we observed that children spent various amounts of time standing independently before the initiation of walking. The correlation analysis indicated that there was a strong relationship between the initiation time and the CoM range in ML during this Initiation Phase. Our participants who demonstrated a smaller range of CoM movement during the Initiation Phase also initiated their walking faster. Those who stood independently for more than a second, however, demonstrated a larger range of CoM movement. These findings suggest that the behavior of the child's CoM, particularly in the ML direction, is related to the latency with which the child initiates the first step. While our results revealed a strong relationship in the latency data, we could not determine whether those children who stood longer needed to balance themselves first before beginning to walk, or decided to stand longer before initiating the first step.

Breniére, Bril, and Fontaine (1989) suggested that the gait initiation process is a result of an initial fall forward. Furthermore, the anticipatory behavior of the gait initiation has been found in adults (Brenière, Cuong Do, & Bouisset, 1987) and in children (Bril et al., 2015; Ledebt, Bril, & Breniére, 1998), in which the center of pressure shifts posteriorly toward the stepping leg then laterally toward the stance leg, creating a distance between CoM and CoP to produce propulsive force to move body forward. It is possible that those children who demonstrated a larger range of CoM movement in the ML direction needed a longer time to transform body sway into forward stepping. However, such anticipatory behavior is not significantly observed in young children of the age of our participants (Breniére et al., 1989). Therefore, to test this hypothesis, a more in-depth examination is needed of how adults assist their child in standing, influencing the relationship between their child's CoM and CoP, and how their child responds and initiates their first step.

The individual examples contrasted ways in which adults assisted their children in standing and in preparation for walking. We discovered individual differences in the assistive forces, duration of assistance, and behavior of the children's CoM. This individual variability provides direction for our purpose of developing assistive robotic devices to assist developmentally delayed children in standing and walking. While each child performed differently, adults all first provided the assistive forces, which were tailored to the child's behavior, to stabilize the child in both AP and ML directions. Once the child was stabilized, adults reduced the assistive forces to allow the child to change the directionality of the CoM movement to sway more in the AP direction. This directional change is critical in facilitating the initiation of walking as it could allow the child to transform body sway into forward stepping. After the release of support from the adult, the relationship between the range of CoM in ML direction and the initiation time further suggests the importance of transforming the ML body movement to forward stepping to initiate gait. With this information, we could design our assistive robotic devices to emulate the role of the adult by supporting the child and regulating the child's ML and AP sway through the cable attachments to a garment worn by the child (Park et al., 2017). By monitoring the child's CoM movement and modulating the cabling system dynamically, our assistive robotic devices could not only assist the child in standing using a greater force, but also shift the child's ML and AP body sway interchangeably, with a lesser force, to facilitate the transformation of body sway into forward stepping.

One of the limitations of this study is that we did not evaluate how children manage forces acting on the body while standing, without adults' assistance. Additional data addressing this question may provide further insight into the fit between the child's intrinsic capability, and the way that their parent adjusts assistive behavior to their child's developmental achievements. Furthermore, with trials of children, without adults' assistance, losing balance in standing or failing to initiate the first step of walking could allow us to determine the amount of assistance their parents have to provide to keep them balanced. Lastly, there could be different ways for adults to assist their child in standing (e.g., supporting the child at the hands or under the arms). Nevertheless, we designed our instrumented gloves so adults had to hold their child at the hips for two reasons: (a) supporting the hips could be important to the control of the ML stability (Roden-Reynolds et al., 2015); and (b) measuring the interactive force at the hips could guide our assistive robotic devices to regulate the child's ML and AP sway through cable attachments to the hip garment.

Conclusion

Our findings reveal that the adult modulates the forces applied to the child's body in order to assist the child in standing, and to help prepare the child for walking. Moreover, the adult regulates the directionality of the child's CoM movement in the horizontal plane during assistance. This supports the hypothesis that the adult's role in assisting the child in learning to walk is a dynamic process which depends on the child's behavior. Finally, modulating the directionality of the child's body motion is critical in transforming the body sway into the initiation of gait.

Acknowledgments

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