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Using accelerometry for measurement of motor behavior in children: Relationship of real-world movement to standardized evaluation

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ABSTRACT

Background: When detected, children with asymmetrical motor impairment are referred for therapeutic interventions to maximize the child's ability to reach their health and developmental potential. Referal is dependent on standardized evaluation, which rarely examines upper extremity (UE) function within the context of real-world activity. Accelerometry provides an efficient method to objectively measure movement in children. The purpose of this study was to compare accelerometry to clinical assessment, specifically the Melbourne Assessment of Unilateral Upper Limb Function-2 (MA-2).

Methods: A total of 52 children between 1–17 years of age with asymmetrical motor deficits and age matched controls participated in this study. Participants wore bilateral accelerometers for 4 x 25 h. The use ratio (UR) and mono-arm use index (MAUI) were calculated to quantify asymmetrical impairment. The Melbourne Assessment of Unilateral Upper Limb Function-2 (MA-2) was administered and compared to accelerometry variables.

Results: The UR and MAUI were significantly different in children with and without deficits. The MAUI was significantly correlated with all domains of the MA-2: accuracy ($r = 0.44$, $p = 0.026$); fluency ($r = 0.52$, $p = 0.006$); dexterity ($r = 0.53$, $p = 0.005$); and range of motion ($r = 0.49$, $p = 0.011$).

Abbreviations: CP, cerebral palsy; MA-2, melbourne assessment of upper extremity function 2; MAUI, mono-arm use index; UE, upper extremity; UR, use ratio

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Conclusions: Our findings suggest a relationship between real-world movement and clinical evaluation.

What this paper adds

This paper contributes new knowledge about the concurrent validity of accelerometry to standard evaluation. These results suggest that real- world movement behavior is related to clinically measured motor capacity, but is a distinct variable that should be considered when evaluating and supporting children with delays in motor development.

1. Introduction

In early childhood, suspected developmental delays are most often reported in gross motor development (Valla, Wentzel-Larsen, Hofoss, & Slinning, 2015). Limitations in current screening methods delay diagnosis, constraining the opportunity for early intervention when neurodevelopment is most rapid (Ciafaloni et al., 2009; Kirton, 2013; Lurio, Peay, & Mathews, 2015). Identifying children with aberrant motor patterns can help increase access to rehabilitation services and is economically advantageous (Heckman, 2006). However, measuring motor deficits in children presents many challenges, and few measures can be used across childhood (Heineman & Hadders-Algra, 2008; Trost, 2007). Clinical observations offer a brief snapshot of the child's motor capacity and can be influenced by many external factors such as time of day, fatigue, distrust of the provider, or child temperament. The child's willingness to participate in the assessment may contribute to differences in scores and interpretation of skills. Self-report measures have recognized challenges, and clinical measures fail to describe the full impact of the motor deficit on real-world activities despite many children with gross motor impairment having significant activity limitations (Beckung & Hagberg, 2002; Bender et al., 2007; Rydz et al., 2006; Taub et al., 2007; Voigt et al., 2007).

Cerebral palsy (CP), characterized by motor deficits, is the most common form of disability in childhood. Children frequently do not receive a diagnosis of CP until they are several years old (Novak et al., 2017). Hemiparesis is the most frequent marker of CP, making asymmetrical deficits a target for early, intensive interventions such as constraint and bimanual therapy; yet, few clinical tools are available that document asymmetrical differences in children and none for infants (Bleyenheuft, Arnould, Brandao, Bleyenheuft, & Gordon, 2015; Krumlinde-Sundholm, Ek, & Eliasson, 2015; Odding, Roebroeck, & Stam, 2006; Ramey et al., 2013; Spittle, Doyle, & Boyd, 2008).

Upper extremity (UE) movement quality of children with CP can be reliably measured by the Melbourne Assessment of Unilateral Limb Function-2 (MA-2)(Randall, Carlin, Chondros, & Reddihough, 2001). The MA-2 has high internal consistency and high interrater and test-retest reliability (Randall et al., 2001; Spirtos, O'Mahony, & Malone, 2011). While the MA-2 can provide important clinical information, it is not always practical for use in clinical practice due to the cost (USD $1,072) and time required to be trained to administer and interpret the assessment with sufficient interrater reliability (Cusick, Vasquez, Knowles, & Wallen, 2005; Randall, Johnson, & Reddihough, 2019). Further, clinician adherence to the assessment protocol can be limited (Bland et al., 2013) suggesting the need for an additional quantitative, objective measure. An objective method to measure real-world movement patterns would allow therapists to identify children who need more comprehensive evaluation and to more precisely target interventions to help children gain motor skills to maximize independence.

Wearable technology can circumvent the challenges of early childhood assessment by offering an exciting opportunity to measure real-world spontaneous activity of children (De Vries et al., 2009; Marcroft, Khan, Embleton, Trenell, & Plotz, 2014). Accelerometry offers a unique method for measuring movements throughout a typical day, rather than only capturing a brief snapshot that may be biased by the clinical setting. Biosensors that capture acceleration of movement can be affordable, lightweight, waterproof and durable. Wearable biosensors have been validated and can accurately detect alterations in motor activity in adult populations following stroke (Bailey & Lang, 2013, 2014; Bailey, Klaesner, & Lang, 2014; Bailey, Klaesner, & Lang, 2015; Sokal, Uswatte, Vogtle, Byrom, & Barman, 2015; Waddell et al., 2017). However, children recover and move differently following brain injury. Research using accelerometers in infants and children has focused on intervention outcomes and lower extremity movement (Abrishami et al., 2019; Trujillo-Priego & Smith, 2017). Recent work has identified that accelerometers can distinguish children with asymmetrical motor impairment (Hoyt et al., 2019), but it remains unknown whether these real-world motor variables correspond to current standardized measurement tools.

The purpose of this study was to determine the construct validity of real-world movement measured with accelerometry when compared to upper extremity function measured with the MA-2, a highly utilized pediatric assessment. A greater understanding of the relationship between real-world activity and clinical evaluation will have valuable implications for evaluation and may facilitate efficient screening for intervention.

2. Methods

This study was a cross-sectional analysis of motor activity and function in children. Approval was obtained from the Institutional Review Board at Washington University School of Medicine between June 2014 and December 2017. Informed consent was provided by the parent or legal guardian of all participants. Children over seven years of age provided written assent.

2.1. Participants

A total of 52 children were included in this study. Children 1–17:11 years of age (26 typically developing controls and 26 with diagnosed CP with hemiparesis from brain injury) were recruited at St. Louis Children's Hospital and Ranken Jordan Pediatric Bridge Hospital in St. Louis, MO. Children were excluded if the family did not speak English, were unable to return devices to a FedEx mailbox, had participated in the current study in the previous 12 months, had orthopedic surgery in the previous six months or if the child had received botulinum toxin injections in the previous three months. A total of five children with CP participated twice at different ages. Children with hemiparesis were age and gender matched to a cohort of typically developing controls that were previously analyzed for a total of 52 children included in this study (Hoyt et al., 2019). All children had a minimum of 75 h of usable accelerometry data. Children with hemiparesis completed a clinical motor evaluation. Demographic information was collected for both cohorts using REDCap (Research Electronic Data Capture) and is outlined in Table 1 (Harris et al., 2009). Compensation was provided to caregivers for their time.

2.2. Measures

2.2.1. Real-world activity with accelerometry

Upper extremity movement throughout the child's day was measured with bilateral wrist accelerometers worn in 25 -h increments, for up to 100 h. We selected the Actigraph wGT3X (ActiGraph, wGT3X-BT; ActiGraph LLC,Pensacola, FL) accelerometer for this study since it the most commonly used device in pediatric research (Trost, McIver, & Pate, 2005). The accelerometers are about the size of a wristwatch, weigh 19 g, have a battery life of approximately 25 days, and are water resistant up to 1 m. To facilitate wearing adherence, accelerometers were donned by research staff using one-time use wrist bands that were color-coded to distinguish between devices worn on the right and left wrists. Caregivers were provided with pre-paid envelopes to return the devices. Data were sampled at 30 Hz using a triaxial accelerometer sensitive to ± 6 g-force. Based on previous methods, data were stored as activity counts where 1 count = 0.001664 g (Bailey & Lang, 2013; Hoyt et al., 2019). The 30 Hz data were binned into one-second epochs. For each epoch, activity counts were combined across three axes $\sqrt{(x^2 + y^2 + z^2)}$ into a single vector magnitude.

2.2.2. Melbourne assessment of upper extremity Function-2 (MA-2)

The MA-2 is a widely used, criterion-referenced measure of the quality of UE movement in children (Randall, Imms, & Carey,

Table 1
Demographics of Participants.

		Hemiparesis (n = 26)	Typically Developing (n = 26)
Children		N (%)	N (%)
Age, yrs. (mean, range)		8.05 (1.92–16.42)	8.04 (2.08–16.42)
Sex			
	Male	13 (50)	13 (50)
	Female	13 (50)	13 (50)
Hand Dominance			
	Right	5 (19)	23 (92)
	Left	21 (81)	2 (8)
Race/Ethnicity			
	White	23 (88)	23 (88)
	Multi-Racial	0	1 (4)
	Not reported	3 (12)	2 (8)
Parents			
Marital Status			
	Married	20 (76)	20 (76)
	Divorced/Separated	0	1 (4)
	Single/Not Married	3 (12)	3 (12)
	Not reported	3 (12)	2 (8)
Highest Education Level			
	Doctoral/Professional	3 (12)	13 (50)
	Master's	8 (31)	3 (12)
	Bachelor's	8 (31)	4 (15)
	Associate's/Some College	4 (15)	4 (15)
	High School	0	0
	Not reported	3 (12)	2 (8)
Number of Children in Home			
	≥ 3	5 (19)	13 (50)
	2	8 (31)	4 (15)
	1	7 (27)	3 (12)
	0/Not reported	6 (23)	6 (23)

Notes. Yrs. = years.

2012). The MA-2 consists of 14 items that ask the child to demonstrate reach, grasp, manipulation and release of objects using movements that mimic functional tasks such as rotating a block, reaching behind their head or picking up a small food pellet (Randall, Imms, & Carey, 2008). The child's performance of the items are videotaped and scored using a three, four or five-point scale based on the child's movement accuracy, fluency, dexterity and range of motion specific to each item. Scores are converted into a percentile for each of the four domains, no total score is produced. The MA-2 has established reliability and validity and was used to measure the clinical motor capacity of children with hemiparesis (Randall et al., 2001, Randall et al., 2008, 2012; Spirtos et al., 2011). Video analysis and scoring was completed by two trained graduate students (S.B. and S.S.) and interrater reliability (ICC = 0.85) was established following published training procedures (Cusick et al., 2005).

2.3. Procedures

Children with hemiparesis came to the Washington University medical campus for a motor evaluation completed by an occupational therapist (CH) or trained graduate student (SB, SS, MB) using the MA-2. Children were fitted with two accelerometers attached to their wrists using one-time use plastic or paper bracelets (Fig. 1). The bracelets were labeled and color-coded to distinguish which device was worn on the right or left wrist. Visual instructions were provided to help parents don the devices, and extra bracelets were provided. Primary caregivers were asked to report if the wristbands were removed for any reason throughout the wearing time. Research team contact information was provided to caregivers if any questions or concerns arose. Accelerometers were returned in-person or mailed using a pre-paid envelope.

2.4. Data analysis

Accelerometry data were processed using MATLAB Version 2015a and analyzed using publicly available custom software (https://gitlab.com/DosenbachGreene/aloha/) written in Python 3.6 (MATLAB & Statistics Toolbox (Version Release 2015a), 2015MATLAB & Statistics Toolbox (Version Release 2015a), 2015; Python Software Foundation (Version 3.6), 2019). Statistical analyses were completed using R Version 3.5.3 (RCoreTeam, 2019). To ensure data quality, the first and last 30 min were removed from each 25 h wear period to account for adjustment or early removal and data were visually inspected for irregularities in activity counts and wear time.

Moments were classified as having movement when the activity count > 2 (Bailey et al., 2014; Gitendra Uswatte et al., 2000). The use ratio (UR) was calculated by summing the seconds of movement (unilateral + bilateral movement) and dividing the total activity of the non-dominant upper extremity (UE) by the total activity of the dominant UE (van der Pas, Verbunt, Breukelaar, van Woerden, & Seelen, 2011). A UR close to 1 indicates approximately equal amounts of activity in both UE's, whereas a UR greater than 1 would indicate more use of the non-dominant UE (Bailey & Lang, 2013; Uswatte et al., 2006). In healthy adults, the mean UR is 0.95 ± 0.06 (Bailey & Lang, 2013).

Because motor evaluation consisted of independent, unilateral movements, we also calculated the mono-arm use index (MAUI) to describe the intensity and frequency of activity of each upper limb in independent movements (Hoyt et al., 2019). As with the UR, each second was classified as having movement if the activity count > 2. Independent movements reflect seconds when one UE recorded movement, while the opposite UE did not. The MAUI ratio reflects the sum of the magnitude of independent, or unilateral movements of the non-dominant UE divided by the dominant UE (Formula 1).

$$MAUI = \frac{\sum_{n \in N, A_{dom}(n)=0} A_{nondom}}{\sum_{n \in N, A_{nondom}(n)=0} A_{dom}} \quad (1)$$

Since the focus of this study was on children with unilateral UE motor deficits, we also used the MAUI to compare clinical evaluation of unilateral deficits to real-world unilateral movement. For each participant with hemiparesis, the items of the MA-2 were scored and translated into a total percentage for each of the four domains (range of motion, dexterity, fluency and accuracy). Descriptive statistics and t-tests were used to describe differences between groups. Pearson's product-moment correlations were calculated to compare each participants MA-2 scores to real-world activity summarized with the UR and MAUI.

Fig. 1. Two three-year-old children wearing accelerometers on both wrists using one-time use color-coded wrist bands. On the left is a girl with CP using plastic bands, and on the right is a boy who was typically developing who preferred paper bands.

3. Results

Our results corroborated previous reports that hemiparesis is associated with a lower UR than controls (mean = 0.75, SD = 0.11; mean = 0.96, SD = 0.05 respectively). This difference was statistically significant (t = -8.70, $p < 0.001$). As seen in Fig. 2, the MAUI was also significantly lower (t = -9.51, $p < 0.001$) in children with hemiparesis than children who were typically developing (mean = 0.23, SD = 0.18; mean = 0.82, SD = 0.26 respectively). The lower UR and MAUI scores suggest that typically developing children used both UEs more frequently for independent movements whereas children with hemiparesis depended largely on their dominant UE for independent movements.

Children with hemiparesis obtained the highest scores on the MA-2 in accuracy (mean = 74.81, SD = 28.64) followed by fluency (mean = 69.64, SD = 24.87), range of motion (mean = 67.59, SD = 24.94) and dexterity (mean = 56.88, SD = 28.15). Because the MA-2 evaluates unilateral movement of the affected upper extremity, the MAUI was selected to compare accelerometry variables to clinical testing. The MAUI was most significantly correlated with the MA-2 domains of dexterity (r = 0.53, $p = 0.005$) and fluency (r = 0.52, $p = 0.006$), with statistically significant but weaker correlation with range of motion (r = 0.49, $p = 0.011$) and accuracy of movement (r = 0.44, $p = 0.026$) which is summarized in Table 2. These moderate correlations between the MAUI and MA-2 subscores indicate that as scores increased on the MA-2 domains, unilateral movement for the affected UE increased as well. In Fig. 3, there are four points in each MA-2 domain that represent individuals who had a diagnosis of hemiparesis but demonstrated MAUI scores (mean = 0.62) similar to their typically developing peers which is highlighted by the overlap of MAUI scores observed in Fig. 2. Children with hemiparesis and high MAUI also scored high in each of the MA-2 domains, demonstrating that they were not significantly impaired.

4. Discussion

Accelerometers are increasingly being explored as a supplement to traditional motor evaluation (Rowe & Neville, 2019; Yang & Hsu, 2010), yet to our knowledge, concurrent validity with clinical assessment of motor capacity has not yet been documented across childhood. We found that both the MAUI and UR were able to separate children with and without asymmetric deficits (MAUI: t = 9.51, $p < 0.001$; UR: (t = -8.70, $p < 0.001$)). Interestingly, we identified that some children with hemiparesis diagnosed with brain injury demonstrated MAUI scores similar to their typically developing peers and these children also scored high on each domain of the MA-2, indicating that their delays were milder than other participants. Based on these findings, accelerometry may serve as a useful tool to efficiently and objectively measure real-world UE movement and approximate the extent of disability that a child may be experiencing. Accelerometry variables such as the UR and MAUI may serve as a useful indicator for costly and time intensive interventions and help determine whether a constraint-based approach or intensive bilateral approach may be warranted.

Comprehensive evaluation is costly, time consuming and requires highly trained therapists to administer and interpret observations. Time intensive interventions to improve motor capacity have documented benefits for many children, but identifying indicators of therapeutic success remains a challenge. How a child uses their UE in the context of everyday life may be a meaningful outcome that can be measured with accelerometry. Accelerometers can be used many times, and only take a few minutes to set up, don on the participant and download data once they are returned. Compared to clinical assessment, accelerometry offers a quick, easy and cost effective method for therapists to screen children for how asymmetric motor deficits manifest throughout a child's typical

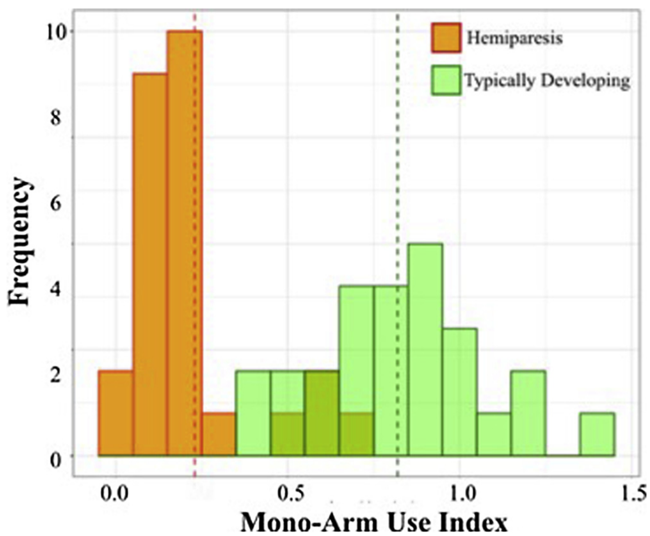

Fig. 2. This histogram reflects the use ratio of all participants (n = 52) in bins of 0.10. Orange bars indicate children with hemiparesis (mean = 0.23) and green indicates typically developing children (mean = 0.82). The mean for each group is indicated with a dashed line. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Table 2
Correlation of Accelerometry Variables to the Melbourne Assessment of Upper Extremity Function-2 Domains.

Mono Arm Use Index	r	CI	p-value
Accuracy	0.44	(0.06,0.70)	0.026
Fluency	0.52	(0.17,0.76)	0.006
Dexterity	0.53	(0.18,0.76)	0.005
Range of Motion	0.49	(0.13,0.74)	0.011
Use Ratio	r	CI	p-value
Accuracy	0.38	(−0.02,0.67)	0.06
Fluency	0.56	(0.22,0.78)	0.003
Dexterity	0.51	(0.16,0.75)	0.007
Range of Motion	0.53	(0.17,0.76)	0.006

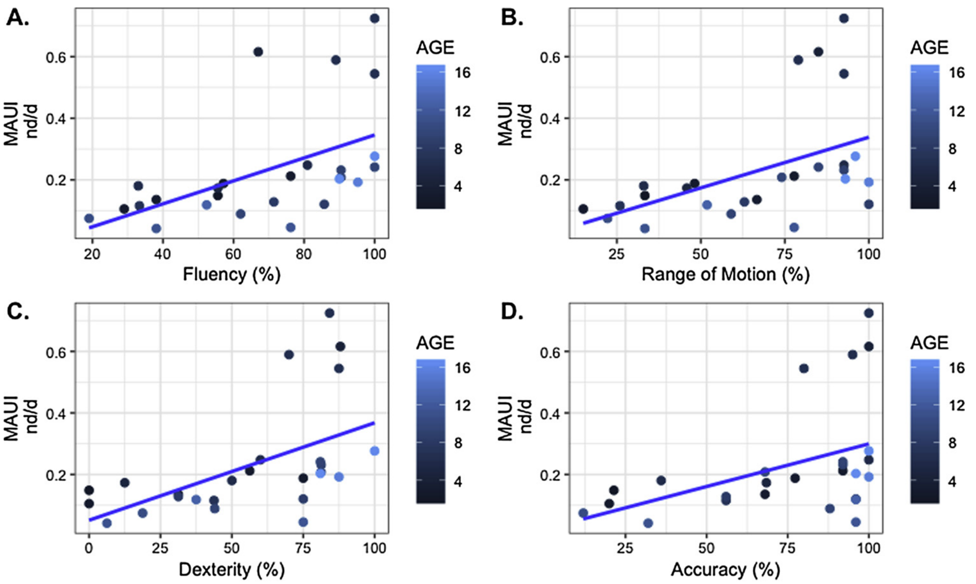

Fig. 3. Scatterplots highlighting the correlation between the mean each domain of the Melbourne Assessment of Upper Extremity Function and the mean mono-arm use index for each child. Points represent children with asymmetrical deficits (n = 26) that completed motor evaluation with the MA-2 and accelerometry protocol.d = dominant UE; nd = non-dominant UE; MAUI = mono-arm use index.

day. These findings demsontrate a relationship between accelerometry and clinical evaluation, and provide initial evidence that accelerometry may be a useful part of advanced evaluation methods. With objective and affordable methods to identify aberrancies in motor behavior affecting real-world movement, rehabilitation providers will have greater ability to provide intervention services to those who could benefit.

The most important finding of this study is that accelerometry variables (UR and MAUI) had a statistically significant correlation to scores in each of the four MA-2 domains. Given this important finding, accelerometry could be used as an option for rehabilitation providers to better understand asymmetrical motor patterns in children with hemiparesis and how the motor impairments affect their motor capacity to engage in activities of daily living. These findings suggest that accelerometry can have an important role in clinical evaluation and may even facilitate more efficient screening and referral of children who could most benefit from intensive intervention.

Another important finding from this study is that the MAUI score had the strongest correlation with the dexterity (r = 0.53) domain of the MA-2, which also had the lowest mean score across participants, indicating that the greatest impairment was observed in this domain. The correlation between dexterity and the MAUI is notable because accelerometers are measuring the movement of the upper limb, and do not directly capture finer hand movements. Yet, children experienced the greatest level of impairment in using their affected UE for highly dexterous movements such as rotating a block. It is not surprising that the MAUI, which represents independent movement of each UE, then has a strongest relationship with clinical measures that correspond to functional disability.

As with any study, methodological limitations limit generalizability. Given that our study used accelerometry as a measure of movement of the upper extremity at the wrist, one would not expect a strong correlation with the domain scores from the MA-2 which describe overall quality of movement and fine motor skill. The moderate correlations identified in this study indicate a relationship, rather than an overlap of constructs, indicating that accelerometry is measuring a related but not identical construct. Additionally, our cohort spanned a large age range (1.9–16.4 years) and it is possible that the developmental stage of the child might impact the relationship between accelerometry and clinical assessment. Children from both cohorts were reported to be predominantly white, living with both parents and in households where the primary caregiver had a college education or higher. To maximize participation and reduce the study burden we allowed caregivers to select the days and times that the accelerometers were worn. As such, some children wore accelerometers only on weekdays or weekends which may be a contributing factor to independent arm use. Future studies should look at larger sample sizes so that the impact of age can be analyzed and standardize when the accelerometers are worn.

5. Conclusions

Based on these findings, accelerometry has the potential to be an effective screening tool for assessing asymmetrical motor patterns that affect participation in activities of daily living. The MAUI provides an exciting new metric that corresponds to the domains of the MA-2, providing the necessary construct validity of accelerometry metrics to this highly regarded measure of upper extremity function in children. Future studies should determine if the MAUI is related to other domains affecting children with CP including challenging behavior, cognition or changes in movement and activity following intensive intervention. Future research should consider using accelerometry along with clinical measures to describe the real-world use along with the quality and movement capacity of the upper extremity.

Authors' contributions

CH contributed to the study design, data collection, analysis, interpretation and major manuscript preparation. SB interpreted the data and was a major contributor in writing the manuscript. SS was a major contributor in data collection, analysis and interpretation. MB contributed to the data collection, analysis and interpretation. AN and MO contributed to study design and data analysis. AN contributed to study design and data collection. CL and BS made substantial contributions to the study design, analysis and interpretation of the data. ND contributed to the study design, data collection, analysis and interpretation. ND was a substantial contributor to manuscript preparation. All authors read and approved the final manuscript.

Declaration of Competing Interest

Authors have no conflicts of interest to report. Funding organizations were not responsible or involved with design and conduct of the study; collection, management, analysis, and interpretation of the data; preparation, review, or approval of the manuscript; and decision to submit the manuscript for publication.

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References

Abrishami, M. S., Nocera, L., Mert, M., Trujillo-Priego, I. A., Purushotham, S., Shahabi, C., ... Smith, B. A. (2019). Identification of developmental delay in infants using wearable sensors: Full-day leg movement statistical feature analysis. *IEEE Journal of Translational Engineering in Health and Medicine, 7*, 2800207. https://doi.org/10.1109/JTEHM.2019.2893223.

Bailey, R. R., Klaesner, J. W., & Lang, C. E. (2014). An accelerometry-based methodology for assessment of real-world bilateral upper extremity activity. *PloS One, 9*(7), e103135. https://doi.org/10.1371/journal.pone.0103135.

Bailey, R. R., Klaesner, J. W., & Lang, C. E. (2015). Quantifying real-world upper-limb activity in nondisabled adults and adults with chronic stroke. *Neurorehabilitation and Neural Repair, 29*(10), 969–978.

Bailey, R. R., & Lang, C. E. (2013). Upper-limb activity in adults: Referent values using accelerometry. *Journal of Rehabilitation Research and Development, 50*(9), 1213–1222. https://doi.org/10.1682/JRRD.2012.12.0222.

Bailey, R. R., & Lang, C. E. (2014). Upper extremity activity in adults: Referent values using accelerometry. *Journal of Rehabilitation Research and Development, 50*(9), 1213.

Beckung, E., & Hagberg, G. (2002). Neuroimpairments, activity limitations, and participation restrictions in children with cerebral palsy. *Developmental Medicine and Child Neurology, 44*(5), 309–316.

Bender, B. G., Bartlett, S. J., Rand, C. S., Turner, C., Wamboldt, F. S., & Zhang, L. (2007). Impact of interview mode on accuracy of child and parent report of adherence with asthma-controller medication. *Pediatrics, 120*(3), e471–477. https://doi.org/10.1542/peds.2006-3457.

Bland, M. D., Sturmoski, A., Whitson, M., Harris, H., Connor, L. T., Fucetola, R., ... Lang, C. E. (2013). Clinician adherence to a standardized assessment battery across settings and disciplines in a poststroke rehabilitation population. *Archives of Physical Medicine and Rehabilitation, 94*(6), 1048–1053. https://doi.org/10.1016/j.apmr.2013.02.004 e1041.

Bleyenheuft, Y., Arnould, C., Brandao, M. B., Bleyenheuft, C., & Gordon, A. M. (2015). Hand and arm bimanual intensive therapy including lower extremity (HABIT-ILE) in children with unilateral spastic cerebral palsy: A randomized trial. *Neurorehabilitation and Neural Repair, 29*(7), 645–657. https://doi.org/10.1177/1545968314562109.

Ciafaloni, E., Fox, D. J., Pandya, S., Westfield, C. P., Puzhankara, S., Romitti, P. A., ... Moxley, R. T. (2009). Delayed diagnosis in duchenne muscular dystrophy: Data from the Muscular Dystrophy Surveillance, Tracking, and Research Network (MD STARnet). *Jornal de Pediatria, 155*(3), 380–385. https://doi.org/10.1016/j.jpeds.2009.02.007.

Cusick, A., Vasquez, M., Knowles, L., & Wallen, M. (2005). Effect of rater training on reliability of Melbourne Assessment of Unilateral Upper Limb Function scores. *Developmental Medicine and Child Neurology, 47*(1), 39–45.

De Vries, S. I., Van Hirtum, H. W., Bakker, I., Hopman-Rock, M., Hirasing, R. A., & Van Mechelen, W. (2009). Validity and reproducibility of motion sensors in youth: A systematic update. *Medicine and Science in Sports and Exercise, 41*(4), 818–827. https://doi.org/10.1249/MSS.0b013e31818e5819.

Harris, P. A., Taylor, R., Thielke, R., Payne, J., Gonzalez, N., & Conde, J. G. (2009). Research electronic data capture (REDCap)–a metadata-driven methodology and workflow process for providing translational research informatics support. *Journal of Biomedical Informatics, 42*(2), 377–381. https://doi.org/10.1016/j.jbi.2008.08.010.

Heckman, J. J. (2006). Skill formation and the economics of investing in disadvantaged children. *Science, 312*(5782), 1900–1902. https://doi.org/10.1126/science.1128898.

Heineman, K. R., & Hadders-Algra, M. (2008). Evaluation of neuromotor function in infancy–a systematic review of available methods. *Journal of Developmental & Behavioral Pediatrics, 29*(4), 315–323.

Hoyt, C. R., Van, A. N., Ortega, M., Koller, J. M., Everett, E. A., Annie, L. N., & Dosenbach, N. U. F. (2019). Detection of pediatric upper extremity motor activity and deficits with accelerometry. *JAMA Network Open, 2*(4), https://doi.org/10.1001/jamanetworkopen.2019.2970.

Kirton, A. (2013). Modeling developmental plasticity after perinatal stroke: Defining central therapeutic targets in cerebral palsy. *Pediatric Neurology, 48*(2), 81–94. https://doi.org/10.1016/j.pediatrneurol.2012.08.001.

Krumlinde-Sundholm, L., Ek, L., & Eliasson, A. C. (2015). What assessments evaluate use of hands in infants? A literature review. *Developmental Medicine and Child Neurology, 57*, 37–41. https://doi.org/10.1111/dmcn.12684.

Lurio, J. G., Peay, H. L., & Mathews, K. D. (2015). Recognition and management of motor delay and muscle weakness in children. *American Family Physician, 91*(1), 38–44.

Marcroft, C., Khan, A., Embleton, N. D., Trenell, M., & Plotz, T. (2014). Movement recognition technology as a method of assessing spontaneous general movements in high risk infants. *Frontiers in Neurology, 5*, 284. https://doi.org/10.3389/fneur.2014.00284.

MATLAB and Statistics Toolbox (Version Release 2015a) (2015). *Natick, Massachusettes.* United States: The MathWorks, Inc.

Novak, I., Morgan, C., Adde, L., Blackman, J., Boyd, R. N., Brunstrom-Hernandez, J., ... Badawi, N. (2017). Early, accurate diagnosis and early intervention in cerebral palsy: Advances in diagnosis and treatment. *JAMA Pediatrics*. https://doi.org/10.1001/jamapediatrics.2017.1689.

Odding, E., Roebroeck, M. E., & Stam, H. J. (2006). The epidemiology of cerebral palsy: Incidence, impairments and risk factors. *Disability and Rehabilitation, 28*(4), 183–191. https://doi.org/10.1080/09638280500158422.

Python Software Foundation (Version 3.6). Retrieved from http://www.python.org.

Ramey, S. L., Coker-Bolt, P., & DeLuca, S. C. (Eds.). (2013). *Handbook of pediatric constraint-induced movement therapy (CIMT)*. Bethesa, MD: AOTA Press.

Randall, M., Carlin, J. B., Chondros, P., & Reddihough, D. (2001). Reliability of the Melbourne assessment of unilateral upper limb function. *Developmental Medicine and Child Neurology, 43*(11), 761–767.

Randall, M., Imms, C., & Carey, L. (2008). Establishing validity of a modified Melbourne Assessment for children ages 2 to 4 years. *The American Journal of Occupational Therapy, 62*(4), 373–383.

Randall, M., Imms, C., & Carey, L. (2012). Further evidence of validity of the Modified Melbourne Assessment for neurologically impaired children aged 2 to 4 years. *Developmental Medicine and Child Neurology, 54*(5), 424–428. https://doi.org/10.1111/j.1469-8749.2012.04252.x.

Randall, M., Johnson, L., & Reddihough, D. (2019). *How to order the Melbourne Assessment 2.* Retrieved fromhttps://www.rch.org.au/melbourneassessment/how-to-order/.

RCoreTeam (2019). *R: A language and environment for statistical computing (Version 3.5.3).* Vienna, Austria. Retrieved fromhttps://www.R-project.org/.

Rowe, V. T., & Neville, M. (2019). Measuring reliability of movement with accelerometry: Fitbit((R)) versus ActiGraph((R)). *The American Journal of Occupational Therapy, 73*(2), https://doi.org/10.5014/ajot.2019.030692 7302205150p7302205151-7302205150p7302205156.

Rydz, D., Srour, M., Oskoui, M., Marget, N., Shiller, M., Birnbaum, R., ... Shevell, M. I. (2006). Screening for developmental delay in the setting of a community pediatric clinic: A prospective assessment of parent-report questionnaires. *Pediatrics, 118*(4), e1178–1186. https://doi.org/10.1542/peds.2006-0466.

Sokal, B., Uswatte, G., Vogtle, L., Byrom, E., & Barman, J. (2015). Everyday movement and use of the arms: Relationship in children with hemiparesis differs from adults. *Journal of Pediatric Rehabilitation Medicine, 8*(3), 197–206. https://doi.org/10.3233/PRM-150334.

Spirtos, M., O'Mahony, P., & Malone, J. (2011). Interrater reliability of the Melbourne Assessment of Unilateral Upper Limb Function for children with hemiplegic cerebral palsy. *The American Journal of Occupational Therapy, 65*(4), 378–383.

Spittle, A. J., Doyle, L. W., & Boyd, R. N. (2008). A systematic review of the clinimetric properties of neuromotor assessments for preterm infants during the first year of life. *Developmental Medicine and Child Neurology, 50*(4), 254–266. https://doi.org/10.1111/j.1469-8749.2008.02025.x.

Taub, E., Griffin, A., Nick, J., Gammons, K., Uswatte, G., & Law, C. R. (2007). Pediatric CI therapy for stroke-induced hemiparesis in young children. *Developmental Neurorehabilitation, 10*(1), 3–18.

Trost, S. G. (2007). State of the art reviews: Measurement of physical activity in children and adolescents. *American Journal of Lifestyle Medicine, 1*(4), 299–314.

Trost, S. G., McIver, K. L., & Pate, R. R. (2005). Conducting accelerometer-based activity assessments in field-based research. *Medicine and Science in Sports and Exercise, 37*(11 Suppl), S531–543.

Trujillo-Priego, I. A., & Smith, B. A. (2017). Kinematic characteristics of infant leg movements produced across a full day. *Journal of Rehabilitation and Assistive Technologies Engineering, 4*. https://doi.org/10.1177/2055668317717461.

Uswatte, G., Giuliani, C., Winstein, C., Zeringue, A., Hobbs, L., & Wolf, S. L. (2006). Validity of accelerometry for monitoring real-world arm activity in patients with subacute stroke: Evidence from the extremity constraint-induced therapy evaluation trial. *Archives of Physical Medicine and Rehabilitation, 87*(10), 1340–1345. https://doi.org/10.1016/j.apmr.2006.06.006.

Uswatte, G., Miltner, W. H., Foo, B., Varma, M., Moran, S., & Taub, E. (2000). Objective measurement of functional upper-extremity movement using accelerometer recordings transformed with a threshold filter. *Stroke, 31*(3), 662–667.

Valla, L., Wentzel-Larsen, T., Hofoss, D., & Slinning, K. (2015). Prevalence of suspected developmental delays in early infancy: Results from a regional population-based longitudinal study. *BMC Pediatrics, 15*, 215. https://doi.org/10.1186/s12887-015-0528-z.

van der Pas, S. C., Verbunt, J. A., Breukelaar, D. E., van Woerden, R., & Seelen, H. A. (2011). Assessment of arm activity using triaxial accelerometry in patients with a stroke. *Archives of Physical Medicine and Rehabilitation, 92*(9), 1437–1442.

Voigt, R. G., Llorente, A. M., Jensen, C. L., Fraley, J. K., Barbaresi, W. J., & Heird, W. C. (2007). Comparison of the validity of direct pediatric developmental evaluation versus developmental screening by parent report. *Clinical Pediatrics, 46*(6), 523–529. https://doi.org/10.1177/0009922806299100.

Waddell, K. J., Strube, M. J., Bailey, R. R., Klaesner, J. W., Birkenmeier, R. L., Dromerick, A. W., & Lang, C. E. (2017). Does Task-Specific Training Improve Upper Limb Performance in Daily Life Poststroke? *Neurorehabilitation and Neural Repair, 31*(3), 290–300. https://doi.org/10.1177/1545968316680493.

Yang, C. C., & Hsu, Y. L. (2010). A review of accelerometry-based wearable motion detectors for physical activity monitoring. *Sensors (Basel), 10*(8), 7772–7788. https://doi.org/10.3390/s100807772.