2021 43rd Annual International Conference of the
IEEE Engineering in Medicine & Biology Society (EMBC)
Oct 31 - Nov 4, 2021. Virtual Conference

Unlocking Independence: Exploring Movement with Brain-Computer Interface for Children with Severe Physical Disabilities

Erica D. Floreani*[1,2], Danette Rowley[2], Nadia Khan[1], Dion Kelly[1,2], Ion Robu[2]
Adam Kirton[1,2] and Eli Kinney-Lang[1,2]

Abstract— **Children with severe physical disabilities are often unable to independently explore their environments, further contributing to complex developmental delays. Brain-computer interfaces (BCIs) could be a novel access method to power mobility for children who struggle to use existing alternate access technologies, allowing them to reap the developmental, social, and psychological benefits of independent mobility. In this pilot study we demonstrated that children with quadriplegic cerebral palsy can use a simple BCI system to explore movement with a power mobility device. Four children were able to use the BCI to drive forward at least 7m, although more practice is needed to achieve more efficient driving skills through sustained BCI activations.**

Clinical relevance— **This paper highlights the potential of a novel access technology to achieve patient-centered goals in power mobility for children with severe physical impairments who are otherwise neglected as candidates for powered wheelchairs. This paper also demonstrates how a power mobility device can be adapted to be operated by a readily available commercial-grade BCI system.**

I. INTRODUCTION

Children with severe physical disabilities, such as those living with quadriplegic cerebral palsy (QCP), are limited in their ability to move independently and are therefore unable to access and explore their environment. These children face substantial barriers to participation and are at risk for a wide range of secondary impairments in the aspects of development facilitated by independent movement [1], [2]. Early intervention with power mobility (PM), electrically-powered wheelchairs and other ride-on toys or vehicles, can alleviate some of these barriers and reduce the risk of secondary cognitive, social and psychological delays [2], [3], [4], [5]. However, children whose physical disabilities are severe or who have additional sensory or cognitive impairments are often neglected when it comes to PM recommendations and provision. This has been attributed to the difficulty in finding a reliable access method or site for these children, strict criteria defining eligibility by funding agencies, and a lack of training programs and opportunities to teach driving skills [6]. Historically, clinicians have also believed that achieving "normal" ambulation should be prioritized over aided mobility [7], though this is impossible for the most severely affected individuals. Altogether, this results in an under-served population of children with multiple, severe impairments who are left with limited ways to meaningfully participate and interact with the world around them.

Several case studies have recently demonstrated that children with multiple, severe impairments can learn to functionally use and benefit from PM, with the help of dedicated training programs and careful consideration of type and placement of access methods [5], [8], [9], [10]. Novel access methods such as brain-computer interfaces (BCIs) have potential as a solution for children who struggle with more traditional methods such as joysticks or switches. BCIs provide access by acquiring, analyzing and classifying brain activity to translate intention to commands, bypassing the need for voluntary motor control [11]. BCIs have successfully been used by adults to drive powered wheelchairs and other power mobility devices (PMDs), using complex paradigms to yield multiple commands for controlling power, direction and speed [12]. Few BCI-operated PMDs have been tested with end-users with disabilities, although one recent study reported BCI-operated wheelchair control with greater than 99% accuracy for both able-bodied users and those with motor impairments [13].

Up to this point, no studies have investigated BCI-operated PM for children. We previously established that typically developing children [14] and children with perinatal stroke [15] can use simple BCI systems, and that children with QCP can use BCI to play video games [16]. In this pilot study, we demonstrate that children with QCP can use a simple BCI system to explore movement using a PM training device. We show how a basic PMD can be outfitted to be "BCI-enabled" using commercial-grade technology, altogether laying the foundation for BCI to be explored as a method to access PM and allow severely disabled children to achieve new levels of independence.

II. METHODS

A. Participants

Five children with severe QCP ($\overline{age}$ = 11.4±2.4 years, 1 female) were recruited from our clinical paediatric BCI program, *BCI4Kids* (www.bci4kids.com). All children had a Gross Motor Function Classification (GMFC) score of 5, and 1-3 years of BCI experience through the BCI4Kids program. Two participants have prior experience with PM but are inconsistent users, another has limited ability to operate a manual chair, and the other two have no experience with independent mobility, manual or powered. Assent and parental consent were obtained in accordance with the Conjoint Health Research Ethics Board, University of Calgary.

*Corresponding author. Email: edflorea@ucalgary.ca
[1]Department of Paediatrics, Cumming School of Medicine, University of Calgary, Calgary, AB, Canada, T2N 1N4
[2]Alberta Children's Hospital, Calgary, AB, Canada, T3B 6A8

978-1-7281-1178-0/21/$31.00 ©2021 IEEE

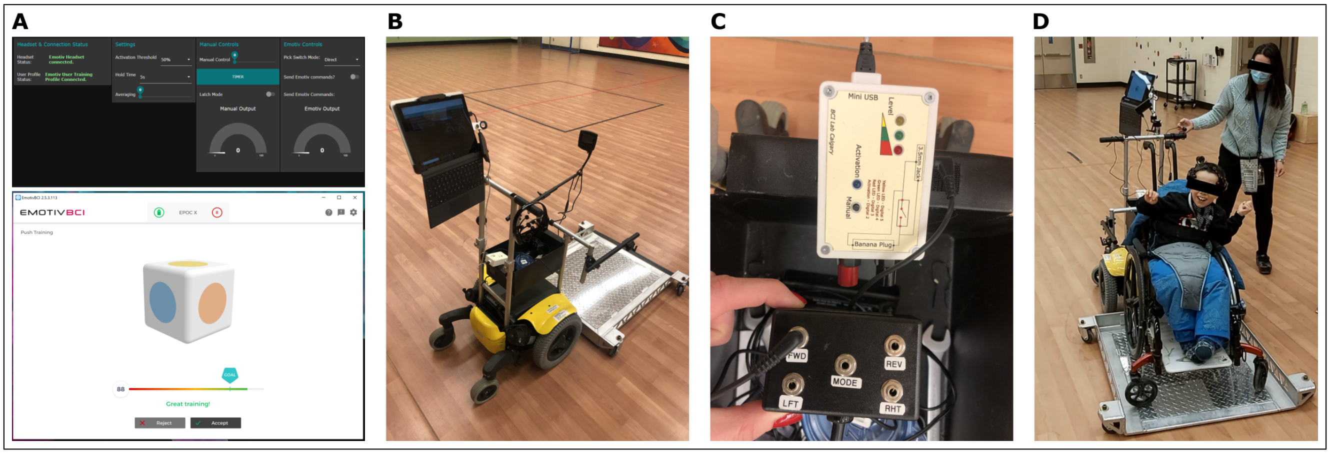

Fig. 1. The BCI-operated power mobility (PM) system. A) The GUI for the Node-RED switch adapter interface (top) and the Emotiv BCI training software (bottom). B) The PM trainer, with a tablet computer mounted for running the BCI software. C) The switch adapter, plugged into the 'forward' control of the PM trainer. D) One of the participants driving the PM trainer.

B. BCI-Operated Power Mobility Device

The PMD used in this study has three parts: the BCI system for interpreting brain activity; the switch interface for translating BCI outputs to traditional PMD access points; and the PM training device.

1) BCI System: A commercial-grade EEG headset, the 14-channel *Emotiv EPOC X*, was used as the signal acquisition modality for the BCI due to its semi-dry electrodes, ease of setup and participant familiarity with the system. The EPOC X and its associated *Emotiv BCI* software can be used to train and practice personalized "mental commands", like imagining pushing or pulling an object. Previous experience in the BCI4Kids program has shown that children with QCP can generate and control these mental commands, despite not having the motor control to execute such tasks. Once trained, the mental commands can be detected and streamed through Emotiv's *Cortex API* to an external application.

2) Switch Interface: To make the BCI-operated PM system as ubiquitous as possible, a switch interface module was developed to translate BCI outputs to switch activations, enabling compatibility with any existing switch-operated device. Detected mental commands from the Cortex API were streamed and translated to the activation of GPIO pins of an *Arduino* board using *Node-Red*, a JavaScript-based programming tool for IoT devices. The Arduino powered a simple circuit with a 3.5mm mono jack plug via a relay. The Arduino and circuitry were packaged in a 3D-printed case, as can be seen in Figure 1C. BCI control could be enabled/disabled and detection thresholds adjusted through a GUI made with Node-Red's dashboard toolbox, shown in Figure 1A.

3) Power Mobility Trainer: PM trainers are tools used by clinicians to train and assess PM skills for potential candidates of powered wheelchairs. The trainer used in this study (Figure 1B) consisted of a wheeled platform powered by a motorized wheelchair base. The user can sit on their manual chair, secured on the platform, and practice driving with their access method. Different speed profiles can be preprogrammed into the trainer, and it has an emergency stop button for safety during training.

C. Study Procedure

Participants attended a single exploratory session at the Alberta Children's Hospital in Calgary, Canada. After a demo of the PMD by the researchers, participants were positioned onto the trainer in their manual chair, fitted with the headset and trained their mental command. Training involved mentally rehearsing the chosen command, e.g., imagining *pushing* the PMD forward, while EEG data was recorded and used to update the BCI's classification algorithm. The training paradigm was repeated at least 3 times, or until a training score of 80% was achieved, as indicated by the Emotiv BCI software. Participants were then prompted to activate and drive the PMD forward across the length of the room using their mental command. The distance and time travelled for at least two trials were recorded, as were the number of BCI activations needed to traverse that distance.

D. Assessments

Participants were asked several questions based on an adapted version of the NASA Task Load Index (NASA-TLX) [17], assessing workload on sub-scales of effort, frustration, perceived control (performance) and temporal demand (timing) using 5-point Likert scales. Participants were also asked how much they enjoyed the activity and if they would like to try it again. Parents were asked how they felt seeing their child drive with BCI, and if they thought continued PM experience with BCI could benefit their child.

III. Results

All five children were able to successfully use the BCI system to activate and drive the PMD forward, consistently activating the BCI to travel at least 7m in one or both of their trials. Their distances, times, and activations, as well as average speed and distance travelled per activation for comparison across participants, can be found in Table 1. Participant 3 used the PMD in a larger space, explaining

TABLE I

TABLE 1: DISTANCES, TIME, AVERAGE SPEED, AND BCI ACTIVATIONS FOR POWER MOBILITY ATTEMPTS.

	Age	Mental Command	Trial #	Speed Profile	Total Distance (m)	Total Time (s)	Avg Speed (m/s)	Avg Speed (km/h)	# of Activations	Avg Distance/ Activation (m)
P1	13	*Waving* right arm	1	1 (slow)	7.40m	112.0s	0.07m/s	0.24km/h	6	1.23m
			2	1 (slow)	7.33m	92.0s	0.08m/s	0.29km/h	7	10.5m
P2	14	*Pushing* PMD	1	1 (slow)	7.24m	35.4s	0.21m/s	0.74km/h	6	1.21m
			2	2 (medium)	4.54m	43.4s	0.11m/s	0.38km/h	5	0.91m
P3	9	*Pushing* PMD	1	1 (slow)	12.50m	78.0s	0.16m/s	0.58km/h	5	2.50m
			2	2 (medium)	18.08m	51.9s	0.35m/s	1.25km/h	6	3.01m
P4	13	*Pushing* PMD	1	1 (slow)	7.20m	187.0s	0.04m/s	0.14km/h	23	0.31m
			2	2 (medium)	7.20m	116.0s	0.06m/s	0.22km/h	12	0.60m
P5	8	*Pushing* PMD	1	1 (medium)	7.20m	39.7s	0.18m/s	0.65km/h	8	0.90m
			2	2 (medium)	7.20m	34.0s	0.21m/s	0.76km/h	4	1.80m

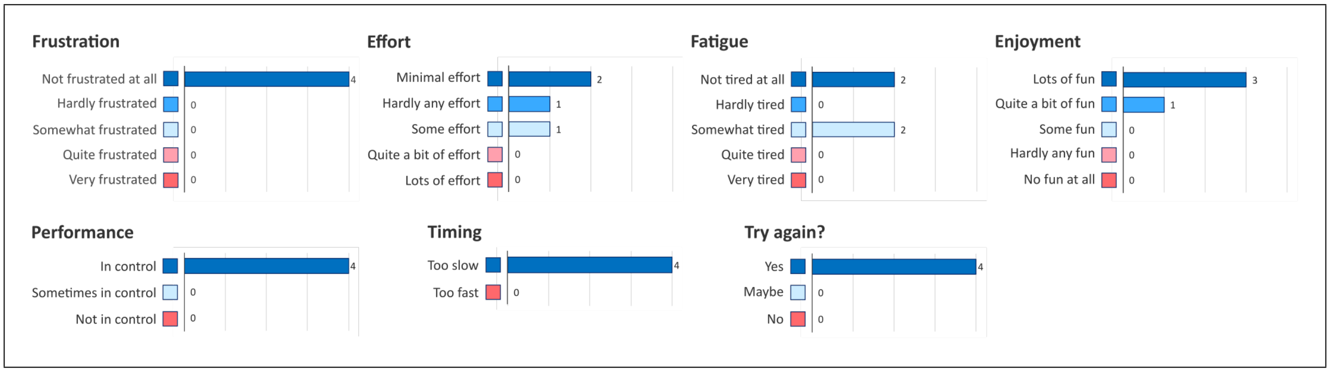

Fig. 2. Adapted NASA-Task Load Index survey results. The number of participants (total n=4) who selected each response are represented by the bar charts for each sub-scale - frustration, effort, fatigue, enjoyment, performance, timing and if the participant wanted to try the activity again. One of the five participants did not answer the survey due to an inability to provide reliable yes/no responses.

their greater distances. The driving speed of the trainer was initially set to a 'low' training speed, then increased to 'medium' if the child wished to move faster. The average speed factors in time spent idle as the child attempted to activate the BCI, and is displayed in km/h in addition to m/s for its greater semantic meaning.

Participant 3 was able to sustain activation of the BCI with their chosen mental command for longer periods of time than the other two participants, as can be seen from their average distance per activation for each trial - up to 3.01m per activation for participant 3, with up to 1.23m, 1.21m, 0.60m and 1.80m per activation for participants 1, 2, 4, and 5, respectively. Participant 4 had difficulty sustaining activation with their mental command, despite observational and verbal confirmation that they were actively trying to engage their command. Participant 4 has been able to successfully use their mental command for other activities in the BCI4Kids program, so we anticipate that they would have experienced greater success in this study with more time spent training the BCI system. The amount and quality of training can impact the ability to accurately detect mental commands and accommodate for changes in baseline brain activity that occur on a day-to-day basis.

Four of the participants answered the adapted NASA-TLX questions using their yes/no response with partner-assisted scanning. The fifth participant could not reliably provide a yes/no response, so they were unable to answer the questionnaire. Responses can be seen in Figure 2. The participants felt little to no frustration while using the BCI to drive the PMD, and felt as if they were in control of the device. The amount of effort needed to drive the trainer ranged from 'minimal' to 'some' effort. Two participants were not tired at all after driving, while the other two felt somewhat tired. All participants felt that the PMD was too slow but reported having either 'quite a bit' or 'lots' of fun, and all four wanted to try using BCI to drive the PMD again. These results indicate that the participants tolerated the task of BCI "driving" well and viewed it as a positive experience with a relatively low workload. All parents reported feelings of excitement seeing their child using BCI to operate the PMD and expressed that using BCI for PM would be beneficial for their child.

IV. DISCUSSION

We have demonstrated that children with severe QCP can use a simple BCI system to explore independent movement with a PMD. This represents the first time, to the author's knowledge, that BCI has been used as an access method for PM for children with severe mobility impairments. With further development and investigation, BCI has the potential to be an alternate access method for children who are unable to use typical methods of accessing PM like switches and joysticks. BCI could also potentially augment PM access for children who can use traditional access methods by providing additional functionality or a possibly less fatiguing option.

While the driving speeds and distances presented in this study are modest, this was each of the participants' first experience using BCI to operate a PMD. Promisingly, each participant demonstrated awareness of cause and effect, acknowledging that executing their mental command would activate the trainer. The three older participants needed very little cueing to attempt activation of the BCI and demonstrated an understanding of how to stop the trainer (mental 'relaxation'). We anticipate that more practice, along with additional calibration and training of the BCI, would allow for the production of longer, sustained activations that would be required for functional driving.

Although the BCI used in this pilot was a simple system offering only unidirectional control over the PMD, this work has laid the foundation for further investigation of BCI-operated PM for children with severe physical disabilities. Future work will involve exploring more complex BCI systems offering multiple commands to allow for directional control, as well as combining BCI with switches or other access methods to provide a customized access solution for each child. The ability to learn BCI driving skills over time and how to best teach these skills should also be investigated, as well as the use of augmented "smart" wheelchair systems to compensate for visual or other sensory impairments in functional driving.

If BCI proves to be unreliable for the level of functional competency required for funded power wheelchair provision, PM experience in the context of play and independent exploration can still be incredibly beneficial [6]. We can see preliminary evidence for this from the participant's positive feedback of the activity, reporting enjoyment and low levels of fatigue, effort, and frustration in the NASA-TLX survey. With all the emerging evidence on the benefits of early independent mobility, clinical perspective is shifting to now advocate PM options for any child with mobility limitations, regardless of their severity of disability or secondary impairments [2], [7]. Further exploring BCI-operated PM fits well within this updated perspective, providing new access options for children with severe physical disabilities, giving them the opportunity to experience the significant cognitive, social, and psychological benefits that come with self-directed, independent movement.

V. CONCLUSION

BCI should be further explored as a novel access method to PM for children with severe motor impairments. The immaturity of BCI technology or the level of disability of the child should not be limiting factors when it comes to providing BCI-enabled PM in supervised, exploratory contexts. There are significant benefits of independent mobility experience within exploration and play even if functional driving abilities cannot be achieved. Further advances in BCI technology, training and implementation of BCI PM skills, and integration of "smart" wheelchair technology or other access methods, will be needed to realize a functional level of BCI-enabled driving for children in the future.

ACKNOWLEDGMENT

The authors would like to thank Al Neary, president of Maximum Healthcare and Mobility Ltd., for providing the power mobility trainer device. We would also like to thank the families of the BCI4Kids program for their continued enthusiasm and support.

REFERENCES

[1] D. I. Anderson, J. J. Campos, D. C. Witherington, A. Dahl, M. Rivera, M. He, I. Uchiyama, and M. Barbu-Roth, "The role of locomotion in psychological development," *Frontiers in Psychology*, vol. 4, no. JUL, pp. 1–17, 2013.

[2] L. Rosen, T. Plummer, A. Sabet, M. L. Lange, and R. Livingstone, "RESNA position on the application of power mobility devices for pediatric users," *Assistive Technology*, vol. 00, no. 00, pp. 1–9, 2018.

[3] R. Livingstone and D. Field, "Systematic review of power mobility outcomes for infants, children and adolescents with mobility limitations," *Clinical Rehabilitation*, vol. 28, no. 10, pp. 954–964, 2014.

[4] M. A. Jones, I. R. McEwen, and B. R. Neas, "Effects of power wheelchairs on the development and function of young children with severe motor impairments," *Pediatric Physical Therapy*, vol. 24, no. 2, pp. 131–140, 2012.

[5] M. Bottos, C. Bolcati, L. Sciuto, C. Ruggeri, and A. Feliciangeli, "Powered wheelchairs and independence in young children with tetraplegia," *Developmental Medicine and Child Neurology*, vol. 43, no. 11, pp. 769–777, 2001.

[6] R. Livingstone and G. Paleg, "Practice considerations for the introduction and use of power mobility for children," *Developmental Medicine and Child Neurology*, vol. 56, no. 3, pp. 210–221, 2014.

[7] L. Wiart and J. Darrah, "Changing philosophical perspectives on the management of children with physical disabilities - Their effect on the use of powered mobility," *Disability and Rehabilitation*, vol. 24, no. 9, pp. 492–498, 2002.

[8] L. K. Kenyon, J. P. Farris, C. Gallagher, L. Hammond, L. M. Webster, and N. J. Aldrich, "Power Mobility Training for Young Children with Multiple, Severe Impairments: A Case Series," *Physical and Occupational Therapy in Pediatrics*, vol. 37, no. 1, pp. 19–34, 2017.

[9] H. H. Huang, C. B. Ragonesi, T. Stoner, T. Peffley, and J. C. Galloway, "Modified toy cars for mobility and socialization: Case report of a child with cerebral palsy," *Pediatric Physical Therapy*, vol. 26, no. 1, pp. 76–84, 2014.

[10] L. K. Kenyon, J. Farris, K. Brockway, N. Hannum, and K. Proctor, "Promoting Self-exploration and Function Through an Individualized Power Mobility Training Program," *Pediatric Physical Therapy*, vol. 27, no. 2, pp. 200–206, 2015.

[11] J. R. Wolpaw, J. d. R. Millán, and N. F. Ramsey, "Brain-computer interfaces: Definitions and principles," *Handbook of Clinical Neurology*, vol. 168, pp. 15–23, 2020.

[12] Fernández-Rodríguez, F. Velasco-Álvarez, and R. Ron-Angevin, "Review of real brain-controlled wheelchairs," *Journal of Neural Engineering*, vol. 13, no. 6, 2016.

[13] A. Cruz, G. Pires, A. Lopes, C. Carona, and U. J. Nunes, "A Self-Paced BCI With a Collaborative Controller for Highly Reliable Wheelchair Driving: Experimental Tests With Physically Disabled Individuals," *IEEE Transactions on Human-Machine Systems*, pp. 1–11, 2021.

[14] J. Zhang, Z. Jadavji, E. Zewdie, and A. Kirton, "Evaluating If Children Can Use Simple Brain Computer Interfaces," *Frontiers in Human Neuroscience*, vol. 13, no. February, pp. 1–7, 2019.

[15] Z. Jadavji, J. Zhang, B. Paffrath, E. Zewdie, and A. Kirton, "Can Children With Perinatal Stroke Use a Simple Brain Computer Interface?" *Stroke*, no. July, pp. 1–8, 2021.

[16] D. Kelly, Z. Jadavji, E. Zewdie, E. Mitchell, K. Summerfield, A. Kirton, and E. Kinney-Lang, "A Child's Right to Play: Results from the Brain-Computer Interface Game Jam 2019 (Calgary Competition)," *Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS*, vol. 2020-July, pp. 6099–6102, 2020.

[17] C. Laurie-Rose, L. M. Curtindale, and M. Frey, "Measuring Sustained Attention and Perceived Workload: A Test with Children," *Human Factors*, vol. 59, no. 1, pp. 76–90, 2017.