This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier’s archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright
Development of robotic mobility for infants: rationale and outcomes

Hélène M. Larin a,∗, Carole W. Dennis b, Sharon Stansfield c

a Department of Physical Therapy, Ithaca College, Ithaca, NY, USA
b Department of Occupational Therapy, Ithaca College, Ithaca, NY, USA
c Department of Computer Science, Ithaca College, Ithaca, NY, USA

Abstract

Objectives To assess the feasibility of a robotic mobility device for infants using alternative control interfaces aimed at promoting early self-initiated mobility, and to assess the effects of a training protocol and robot experience.

Design Observational and pre–post quantitative case studies.

Setting Standardised, research laboratory and day-care centres with toys and individuals familiar to infants.

Participants Children with and without disabilities, aged 5 months to 3 years.

Interventions In each study, infants were seated over a Pioneer TH 3-DX mobile robot. Some infants controlled the directional movement of the robot by weight shifting their body on a Nintendo® Wii Balance Board (the WeeBot), while others used a modified joystick. Infants participated in five sessions over 2 to 5 weeks. Sessions consisted of administering a 10-minute training protocol preceded and followed by 2 to 3 minutes of free play. One child with motor impairment used a button switch array and a different experimental design.

Main outcome measures From the videotaped free-play periods, goal-directed behaviours were coded and time in motion was measured. In the training period, a scoring system was developed to measure the infants’ driving performance.

Results Preliminary outcomes indicate that infants without disabilities, aged 5 to 10 months, demonstrated significant improvement in driving performance and goal-directed movement using the WeeBot. Infants who used the joystick were less successful on all measures. Results for infants with disabilities using the WeeBot were mixed.

Conclusions Mobile robots offer promise to enhance the development of early self-mobility. Novel types of interfaces, such as the WeeBot, warrant further investigation.

© 2012 Chartered Society of Physiotherapy. Published by Elsevier Ltd. All rights reserved.

Keywords: Robotics; Infant; Early intervention; Locomotor activity; Mobility limitation; Rehabilitation

Introduction

In recent years, the field of developmental robotics in paediatric rehabilitation has expanded in different directions to improve the activity and participation levels of children with disabilities and their families [1]. Humanoid robots, such as dolls and pets, are designed to promote social, emotional, communicative, imitative and/or interactive behaviours in children with cognitive and/or physical impairments [2]. Autonomous mobile robots in the form of toys are designed to engage children in active play behaviours or learning activities. Robotic-assistive devices are used to improve independence and quality of life of children with severe physical disabilities. Interface and control methods for these robots include joystick, push buttons, keyboard, laser pointer, switches and touch screen [4,5]. Mobile robots may provide assistance in self-feeding; in reaching, grasping and manipulating toys or objects; and in self-mobility [6]. Access to an independent means of mobility has been shown to benefit a child’s development significantly in various domains [7]. Researchers have developed robotic vehicles with sensors that provide navigation assistance in the form of obstacle...
avoidance, that aid in the performance of certain tasks, or that navigate between sites autonomously [8]. More recently, investigators have explored the feasibility of introducing mobile robots to infants as young as 7 months of age [9]. However, to date, clinical trials with young infants and children trained in using robotic-assisted mobility devices remain scarce; research is ongoing and promising [10].

This paper presents background literature in support of the development of various means of early self-mobility, and the results of studies conducted with infants and young children using mobile robots are discussed. A rationale is offered for a novel means of mobile robot control (the WeeBot) followed by the development of its technology, and results from a series of studies that employed robotic mobility using the Nintendo® Wiimote Balance Board, a joystick and button switches as control interfaces.

Background

Developmental investigators have reported the benefits associated with the onset of infants’ self-initiated mobility. The experience of crawling on hands and knees has been shown to produce greater cortical organisation on electroencephalography in novice crawlers than in prelocomotor infants or long-term crawlers [11]. Infants’ perceptual abilities have been found to undergo a distinct change when they learn to crawl that differs significantly from infants of the same age who do not crawl [7,12]. Eleven-month-old, expert crawlers were found to be more successful than 8-month-old, novice crawlers in their ability to find their mother in a hidden location [13]. Nine-month-old infants with crawling experience also demonstrated more flexible memory retrieval; they were more able to reproduce movement with a novel object in a different context than infants who had not yet crawled [14]. Similar findings were provided in a study of infants with spina bifida. When these infants became independently mobile with the use of an adaptive crawler, they tended to demonstrate better cognitive and physical development, and more advanced parent–infant relationships than infants who had not become mobile [15]. However, when children without disabilities had their mobility restricted for even relatively short periods of time, they showed apathetic behaviour and depressed motivation [16]. Children with physical disabilities and restricted mobility demonstrated similar behaviours, including apathy, increased dependence, lack of curiosity, frustration, depressed motivation and a lack of confidence [16].

The development of self-initiated crawling has also been associated with socio-emotional transformations in the parents and changes in parent–child interaction. For infants aged 6 to 10 months, mother–infant physical distance and style of interaction were reported to change from ‘close, not-face-to-face’ in prelocomotor infants to ‘near, face-to-face’ in infants able to crawl [17]. Maternal behaviours were also found to be related to their beliefs, expectations and anticipations of infants’ self-initiated locomotion, and possibly created “conditions fostering its emergence” [18, p. 299]. Most parents adopt strategies that emphasise safety and challenge that are based on their beliefs about their child’s motor abilities and motor risk-taking; they will allow their child to engage in some slightly risky behaviours [19]. With children with motor impairments, during early intervention, parenting stress has been found to be inversely related to children’s motor abilities [20]. Such factors may have a positive or negative influence on parents’ outlook for their child’s capabilities for self-initiated mobility with assistive devices.

Within research contexts, powered wheelchairs with a joystick interface have been introduced to a few groups of children with varied mobility impairments, some as young as 14 to 20 months of age [21–23]. Children were reported to have gained competent driving skills within about 3 to 6 weeks of use at home. Seven- and 8-month-old infants without disabilities, trained in using a powered mobility device, showed similar postural compensations and emotional expression to infants crawling or using a walker [24]. However, to date, children are usually at least 3 years old when they are provided with a powered wheelchair [25,26]. The rationale for this situation is primarily based on the need for cognitive prerequisites of problem-solving and spatial relations skills [27], and the assumption that the use of powered wheelchairs might interfere with the achievement of higher motor abilities.

The conventional method for driver training of a powered wheelchair is expensive, can be labour intensive, and may require hand-over-hand assistance [25]. A group of 10- to 18-year-olds with muscular dystrophy or cerebral palsy reported that tipping and running into furniture were the most common types of problems encountered [28]. Clinicians from adult and paediatric facilities reported that some users of powered wheelchairs had great difficulty with steering and manoeuvring tasks, and with activities of daily living. While they mentioned the impairments of motor skills, strength or visual acuity as limiting the use of powered wheelchairs, they also indicated that nearly half of the non-users would benefit from an automated navigation system [29]. Parents of children with physical disabilities, whose children learned to use powered wheelchairs, first perceived wheelchairs negatively and reported difficulties with environmental barriers. Over time, however, the parents generally gained a positive view of their children using powered wheelchairs, and noted the children’s increased independence and opportunities to participate in meaningful activities [30]. The support for providing self-mobility devices to younger children has increased substantially based on developmental theories (i.e. intentionality thriving during the second 6 months of life [31], early experience and task repetition needed for performance and learning transfer, and related changes in cortical mapping).
Robotic-assisted mobility controlled by a joystick has been proposed recently as a means to offer earlier mobility and thus minimise the negative developmental effects of motor impairment. Research with infants with disabilities using robotic-assisted mobility is limited, and little success with directional driving has been demonstrated for children under 2 years of age. Preliminary reports on a few cases have been published. A 7-month-old infant without disabilities and a 14-month-old infant with Down’s syndrome seated behind a robot controlled with a reversed joystick, demonstrated increased reaching/pulling on the joystick and increased forward movement of the robot over time [9]. A 7-month old infant with spina bifida, using the same robotic mobile device, was involved in 3–4 training sessions per week over 4 months. Each session consisted of multiple training trials followed by a free exploration period. The infant showed improved driving variables and increased scores on the Bayley III, cognitive ad language, at a greater rate than the infant’s chronological age. However, the infant was not able to control the direction of the mobile robot [32]. At 12 months, the same infant started to use a standard powered wheelchair; and at 2 years, participated in four training sessions over 4 non-consecutive days using a mobile robot with a force-field joystick to follow a path. The child’s deviation from the path and the travel time decreased over this training period [33]. A 3-year-old child with cerebral palsy also participated in four training sessions over 5 non-consecutive days using a force-feedback joystick to follow a path with turns; the child’s performance improved over the 5 days [34].

In another study, 10 children without disabilities (average age 30 months) were divided into two groups: five trained with a force-field joystick (haptic feedback) and five in a control group. Children in the experimental group learned to navigate faster and more accurately through an obstacle course than children in the control group, and required less correcting force over the training trials [33]. Lastly, the feasibility of power mobility as a means to increase socialisation was documented for a 3-year-old child with spastic quadriplegic cerebral palsy interacting in a classroom [35].

Robotic-assisted mobility devices controlled by interfaces other than a joystick have emerged. A control board placed at the side of a robot controlled with a reversed joystick, demonstrated increased reaching/pulling on the joystick and increased forward movement of the robot over time [9]. In the second study, five children aged 34 to 39 months without disabilities and one 49-month-old child with spastic cerebral palsy experienced forward robotic-assisted mobility through leg motion on a stationary board in a supported-standing position [38]. A manual joystick was used for turning the robot. The children travelled back and forth through a maze with three foam barriers. All children successfully completed six trials in the maze over several visits (10 trials for the child with cerebral palsy over 2 days) without extensive training. The authors perceived the device to be a potential way of encouraging gross motor skills development. They are considering replacing the joystick with a control mechanism where children in supported standing would lean or turn their trunk to activate the robot. The children would be assessed using standardised tools and physiological measures. Teams of researchers continue to explore various, original interfaces that may benefit the individual needs of children with physical disabilities.

**Rationale for the WeeBot**

Studies on self-initiated mobility for children with disabilities using powered wheelchairs or assisted robotic devices have used joysticks as the primary interface. Joystick control requires advanced upper extremity skills, hand dexterity and intellect. Dissociation of the upper arm (from the trunk and within the arm), hand grip and eye–hand coordination, conscious attention and cognitive directionality are also required. In designing the control method in the present study, the research team first considered the earlier milestones of reaching with the upper extremity that infants practice in sitting, and the independent sitting achieved at around 6 months of age. Of particular interest was the model of five developmental self-awareness levels by Rochat [39] based on empirical observations of infants’ reactions to mirror reflection. Four- to 6-month old infants without disabilities have been reported to attain level 2, termed ‘situation’ (i.e. the implicit sense of self said to be related to their ability to reach in the sitting position). The infants’ decision to reach for objects placed at various distances and locations was regulated by their level of postural control and adjustment in sitting [39,40]. These considerations led the authors to explore the use of various interfaces, including the Wii Balance Board, as a novel means of control for a mobile robot: the WeeBot. Infants are seated in a secure, upright infant seat with low armrests placed over the Balance Board. They activate a mobile robot through shifting their body weight in their attempt to reach in the direction of a desired toy or person. The authors believe that this strategy triggers the infants’ core proprioceptive, visual, vestibular and balance systems, and frees their upper extremities to reach for objects of interest – an early, instinctive, developmental ability.
Technological development of the WeeBot

The long-term goal of this research programme is to investigate the developmental benefits of providing robotic mobility to infants and young children with physical impairments who are less than 3 years of age. The initial step was to develop a custom system, the WeeBot, that would allow infants to display goal-directed movement (intentionality) [41,42]. An aluminium platform carriage with six casters was designed to fit over a commercially available Pioneer™ 3-DX robot (Pioneer – Adept MobileRobots, 10 Columbia Drive, Amherst, NH 03031 USA) to ensure stability and to support the weight of an infant and commercial seat secured on top of a Wii Balance Board (Fig. 1). A commercial wireless joystick is used by a researcher for master over-ride control to address safety. The WeeBot software, allowing an infant to control the movement of the robot, was developed to run on the robot’s on-board computer. The software monitors eight forward-facing and eight backward-facing sonar sensors to prevent collisions; it also gathers robot motion data from the robot wheel encoders. The Wii Balance Board has responsive pressure sensors in each of its four corners and built in Bluetooth capabilities. The software compares the values of the four pressure sensors to determine which, if any, direction the infant is leaning. When an infant reaches out for an object or a person, the sustained lean is detected and the robot begins to move in that direction. The robotic system is initially calibrated to the characteristics of each infant’s non-leaning posture. These calibration values were used to determine the non-leaning load value thresholds and the percentage of weight displacement needed to constitute a lean. The speed of movement of the robot and the stopping distance needed to avoid collisions may also be defined for each child. In this developmental phase, the feasibility of the WeeBot system was originally tested with three infants without disabilities aged 7 to 9 months. They showed the ability to activate the robot independently as they weight shifted their upper body and leaned to reach for a toy. They were also observed to move spontaneously when they were not prompted to move, although it was not possible to determine whether they realised that their leaning caused the movement of the robot.

WeeBot research: children without disabilities

In a pilot study, five 6- to 9-month-old infants without disabilities, who were not yet crawling on hands and knees, were found to demonstrate directed, purposeful movement of the WeeBot in training and free-play periods [42]. The study was conducted in a standardised indoor environment in five videotaped sessions over 2 to 5 weeks. A protocol of a 10-minute training period with pre and post 2-minute free-play periods was followed. In the training period, the infant was offered toys from three directions (front, right, left) at three distances (6, 12 and 36 inches). A sequence of verbal, tactile and physical cues were given 5 seconds apart, and a scoring system was developed to record the infant’s driving performance. In each of the 2-minute free-play periods, infants were permitted to explore the environment freely without researcher or parent encouragement. Goal-directed behaviours during free-play were coded every 5 seconds, and time in motion was measured in seconds from the videotapes of the sessions. Four of the five infants demonstrated excellent driving performance on the final visit, completing 92% of trials successfully (i.e. were able to drive to the offered toy using tactile and/or verbal prompts). Across all visits, infants were significantly more successful in directing the movement of the robot in the forward direction compared with the left and right directions (Friedman test, \( P = 0.002 \)). Both the goal-directed movement and mean time in motion from the pre and post free-play periods were found to have increased significantly by the final session (t-test: \( P = 0.02 \) and 0.013, respectively). All infants tolerated the sessions well and seemed to enjoy their experience on the mobile robot.

In a follow-up study, 10 infants without disabilities (aged 5 to 8 months, mean age 6 months and 18 days) were studied to expand upon the results of the pilot study discussed above. Participants included three male and seven female infants who had not yet achieved the ability to crawl on hands and knees. The training period for all infants was completed within 2 weeks, and the robot experiences were conducted in
three different settings. The protocol followed the same procedure, and performance was measured in the same manner as in the earlier pilot study. Free-play periods were increased from 2 to 3 minutes. Goal-directed movements (coded for each second) and time in motion were only measured when infants were in control of the WeeBot. When infants were not in control, researchers used the over-ride joystick to re-orient the robot as necessary. Results of preliminary analysis of the data are reported here. Driving performance increased significantly from the first to the last robot experience ($z = -2.703, P = 0.007$). On the final visit, infants were successful on 88% of driver training trials (with verbal or tactile prompts). As in the earlier pilot study, across all sessions, infants were significantly more successful in moving the robot towards a toy in the forward direction compared with the right or left directions (Friedman test: $P = 0.011$). Goal-directed movement also increased significantly from the first to the last session (paired samples $t$-test: $P = 0.048$). Increases in time in motion from the first to the last session were not significant in this study. Infant affect was also measured during the 3-minute free-play sessions on a seven-point scale at 3-second intervals (for a total of 60 intervals). No significant differences in affect were found from the first to the fifth session; however, the overall scores demonstrated a neutral to positive affect in 97% of the intervals.

The research team has started to compare infants’ performance using a joystick with their performance using the Wii Balance Board. Following exploration of different configurations, a commercially-available joystick was modified and positioned between the infants’ legs to control the robot (Fig. 2). Unlike earlier work by Galloway et al. [9], forward movement of the joystick resulted in forward robot motion (with backward motion disabled). To date, five infants under 9 months of age (mean age 7 months and 8 days) have completed five training sessions using this modified joystick, following the same protocol described above. Training sessions were completed over 12 days or less; all robot experiences occurred in the authors’ research laboratory. On the first visit, infants were successful on 9% of driver training trials, compared with 24% of trials on the final visit. As anticipated, the joystick appears to be much more difficult to learn to control than the WeeBot for infants at this age. Additionally, infants seemed to become frustrated with their inability to control robot movement, and the overall effect appears to be more negative than was observed in studies using the WeeBot. This study is ongoing; additional data will be analysed when more infants have completed the study.

WeeBot research: children with disabilities

Two infants with disabilities were also studied using the WeeBot. One was a 15-month-old boy with cerebral palsy who attended a community day-care centre. He was able to sit independently indefinitely but had no means of independent mobility when he began the study. His Gross Motor Function Classification System (GMFCS) [43] level was IV. From his first experience with the robot, he demonstrated good ability to direct its movement. From observations, he appeared to have an active interest in exploring his environment, touching surfaces and exploring drawers within his reach in the kitchen where robot experiences took place. Over his six robot experiences, he completed 85% of driving performance trials successfully (using tactile and/or verbal prompts). His performance was similar at each of the distances at which toys were offered. His performance when toys were offered from the front (100% success) or the left (89%) appeared to be better than when toys were offered from the right (67% success). This is not surprising because his right upper extremity use was more limited than his left. By the end of the study, this child had started to creep, using his elbows to pull himself forward on his stomach (GMFCS level III). Further analysis of data remains to be completed. The second child was a 7-month-old boy with Down’s syndrome who was seen in a private home. He could sit independently for brief periods of time and did not have independent mobility (GMFCS level IV). This child demonstrated little interest in the toys offered, and was generally unsuccessful in controlling the robot, achieving 9% success on both the initial and the final driver training trials. Researchers felt that his responses to requests to ‘get the toy’ were random and not intentional in nature. Responses were equal across distances; success was greater when toys were offered in the forward direction compared with the left or right directions.
Robotic research with an alternate interface: children with disabilities

Some children with disabilities are unable to use a joystick or the Wii Balance Board as interfaces due to motor limitation. A different type of interface was used with a 3-year-old boy with a significant motor impairment associated with spastic-athetoid cerebral palsy [44]. His GMFCS level was V; he could not sit independently nor maintain head control, and his only means of independent mobility was rolling from supine to prone. The child’s receptive language was near age-appropriate level. He could indicate yes and no by extending his left or right arm towards the American Sign Language sign or printed word (provided by an adult just in front of the child). For this child, an adaptive seat with a pelvic belt, chest harness and head support was used. The child’s motor impairment precluded use of the Wii Balance Board control; a series of four buttons was designed as the input device for the WeeBot. The buttons were placed on a custom-made tray in front of the child who could reach them with his right arm/hand. Each button, 1.5 inches in diameter, had a different colour and activated the robot in either the forward, backward, right or left direction. Over a 4-month period, the child participated in 12 videotaped, 1-hour weekly sessions. Most sessions occurred in a research laboratory. However, during a holiday period, the WeeBot was used two additional times in the child’s home. A training protocol similar to the earlier pilot study was attempted but administered inconsistently because of the child’s limited participation, and physical and emotional tolerance level. Sessions consisted primarily of verbal reinforcement by the parent and researchers, and trial-and-error motivating activities. Based on observations from videotaped sessions, in spite of the difficulties, the child increased his willingness to spend time with the mobile robot and gained fair control of forward movement, particularly in self-selected target activities. Steering the robot was very difficult for this child. The authors hypothesised that his motor impairment made it very difficult for him to achieve the timing of the release necessary for directional success. With a button system, the user must press the button to initiate a turn, and release it at the instant that the robot is directed towards the target.

Each of the studies reported above were approved by the All-College Review Board for Human Subjects Research at Ithaca College. All parents/legal guardians signed an informed consent form to allow their child’s participation.

Discussion

From these preliminary results, infants aged less than 10 months without disabilities tolerated training and free-play periods with the WeeBot well, and demonstrated that they were capable of learning to control the robot even at this very early age. Most infants displayed excellent driving performance on the final visit, and intentional, goal-directed movement increased significantly from the first to the final visit. The finding that infants were initially more successful in reaching and moving forwards as compared with moving to the right or left can be associated with the directional development of postural control (i.e. sagittal prior to frontal and transverse planes of movement). The infants’ level of body self-awareness as the means of control of the robot movement, however, appeared to be present and may be associated with Rochat’s [39] level 2 (situation) where infants capable of reaching are sensitive to the situation of their own body in relation to the object for which they are reaching. The WeeBot may have assisted the infants’ development of self-awareness, although this connection was not investigated.

For the two children with disabilities (aged 7 and 15 months) who experienced self-initiated motion with the use of the WeeBot, results of their driving performance were mixed. The age of the children, their level of interest and inner motivation, and their cognitive ability are probable factors for these outcomes. The data suggest that for use of the WeeBot, young children with disabilities may need to have developed some sitting postural control, with minimum motor abilities at level IV on the GMFCS [43] and self-awareness at level 2 (situation) on Rochat’s model [39].

Early results from the comparison of the Wii Balance Board and joystick as interfaces for control of a mobile robot with infants without disabilities reinforces the concept that using the joystick is more complex and less easily learned compared with the WeeBot. The use of the individually-calibrated, computerised Wii Balance Board as an interface to control the robot is viewed as a promising means to promote early self-mobility and possibly body self-awareness in infants with motor impairments. The Wii Balance Board may also encourage infants to gain postural degrees of freedom and move in a wider range of reach than they would otherwise, taking higher risks within a safe and rewarding environment. Parents’ expectations and parent–child interaction may be positively influenced. Given that independent, self-mobility is linked to developmental benefits for infants with and without disabilities, the WeeBot with a Wii Balance Board control interface warrants further investigation.

Acknowledgements

The authors wish to thank the parents and children who participated in the studies, as well as the occupational therapy, physical therapy and computer science students who contributed.

Ethical approval: Ithaca College, All-College Review Board for Human Subjects Research.
Funding: School of Health Sciences and Human Performance, Dean’s Office, and Provost’s Office at Ithaca College, and the National Science Foundation. The sponsors had no involvement in the design, collection, analysis and interpretation of data, writing the manuscript, or the decision to submit the manuscript for publication.

Conflict of interest: None declared.

References


