

Xi Chen

Sherry Liang

Stephen Dolph

Department of Mechanical Engineering,
Mechanical Systems Laboratory,
University of Delaware,
Newark, DE 19716

Christina B. Ragonesi

James C. Galloway

Department of Physical Therapy,
Infant Motor Laboratory,
University of Delaware,
Newark, DE 19716

Sunil K. Agrawal

PhD
Professor
Department of Mechanical Engineering,
Mechanical Systems Laboratory,
University of Delaware,
Newark, DE 19716
e-mail: agrawal@udel.edu

Design of a Novel Mobility Interface for Infants on a Mobile Robot by Kicking

Many infants with special needs, such as with Down syndrome, cerebral palsy, and autism have delayed independent mobility due to weak musculature and/or poor coordination. Children with mobility impairments often do not use powered chairs until the age of five, as per current medical practice. Consequently, these children spend considerably less time moving independently around in their environment compared with typically developing children of the same age. Lack of independent mobility may result in delays in their cognitive, perceptual, social, and emotional development, which are well correlated with locomotion. This paper describes a novel mobility interface for the robot to explore the environment when infants are placed in a prone position. Infants can maneuver the robot through a drive interface that utilizes a camera to detect the motion of markers attached to their legs. We expect that infants will learn to drive the device by swinging their legs. Specifically, this paper demonstrates feasibility of this drive interface using data from two infants. Future studies will determine how infants can be trained to drive a robot purposefully and how such self-generated locomotion affects their long-term development. [DOI: 10.1115/1.4002322]

1 Introduction

Studies show that the onset of independent locomotion, especially crawling on hands and knees, typically occurs around 6 months of age and is a causal factor in major changes in perception, cognition, social, and emotional development [1–3]. Studies show that the rhythmic pattern of crawling is significant for the development of proper physical coordination, the brain, and learning [4]. The lack of crawling has been shown to lead to learning and emotional disabilities and this is why physical therapists discourage the use of devices that take away crawling time, such as the baby walkers and the leg splints. Unfortunately, infants with motor impairments do not get the same opportunity to crawl. Children with mobility impairments also rarely use a powered wheelchair before they are 20 months old due to safety concerns.

Current pediatric crawlers on the market have a platform or suspended support sling on caster wheels. These provide support to the infant torso and reduce required effort on arm and leg muscles [5,6]. Although these crawlers help infants in self-mobility, these may not be suitable for all mobility-impaired infants. In these devices, the infants can only move as much as their musculature and coordination allows, however, their impaired movement capability is not amplified. Crawling motion is additionally beneficial for strengthening core muscles and one such immobile exerciser was recently proposed [7]. Currently, there are no devices that encourage infants to crawl and amplify their small body movements into functional and developmentally relevant motions. However, these objectives can now be satisfied using robotic component technologies such as sensors, motors, power amplification, and control.

Our on-going work at the University of Delaware supports that infants with mobility impairments can learn to drive mobile robots, via joystick, after training [8–10]. Prior results suggest that infants activate a joystick to achieve self-motion [3]. Furthermore, our group showed that an infant with spina bifida can learn to purposefully drive and also improve cognitive, motor, and language skills [9]. A case report studied the effects of early power mobility intervention on a 20 months old girl with spinal muscular atrophy [11]. The subject progressed continually in communication, cognitive, and personal-social skills. The subject achieved independent movement through the use of her wheelchair in only 6 weeks of training.

These positive results with early driving training encourage us to explore robotic technologies to assist infants to be mobile. Our proposed device is “biodriven” and requires body movements to drive. It offers safety by using sonar sensors to detect objects and logic to avoid them. We believe that providing infants, as young as 6 months, the opportunity to be independently mobile may significantly impact their development.

Observations of young infants crawling reveal two modes: (1) younger infants perform homolateral crawling in prone position, where they push off with one foot and pull themselves forward with the hand on the same side, and (2) infants who are closer to the walking stage cross-crawl or contralateral creep, i.e., they move by pulling up one arm and push forward with the opposite foot. Based on this information, we designed our device to allow an infant to explore using both hands and legs to drive the robot. In our design, the infant lies prone on a mobile robot. A motion-capture camera detects markers that are secured to the feet of the infant who lies prone on the device. The device is driven forward by the motion of the feet and is turned to the right or left via a commercial joystick.

Manuscript received October 25, 2009; final manuscript received July 29, 2010; published online September 8, 2010. Assoc. Editor: Ted Conway.

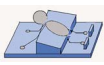


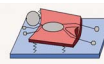
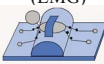
Interface	Method	Benefits	Disadvantages
	- Infant controls robot using the natural limb movements tracked by a mouse in each hand	- Low cost - USB interface - Easily compatible with robot software	- Infants grab mice as toys based on our observation - Limited range of motion
Resistive or Capacitive Tactile Sensors	- Touch screen tracks infant's hand placements and correlates that to robot movement	- Display can be colorful to encourage interaction - USB interface	- Expensive - May not be intuitive to infants - May not stimulate enough exercise
	- Stereo camera tracks infants face to correlate head direction with robot heading - Stereo camera tracks hands or leg movement to set forward velocity	- Easy to push joystick in one direction - USB interface	- Expensive - Long processing/shipping time
	- Track distance that the limbs move and correlate with robot movement	- Easy to get position, velocity and acceleration	- Limited range of motion using linear encoder
	- Sensors placed on flexible board under infant's belly to correlate body movement with robot movement	- Inexpensive - Allows movement without fine motor skills	- Require data acquisition system (additional expenses) - Not readily interfaced through C++
Accelerometers	- Strapped on arms or legs to correlate acceleration of limbs to robot movement	- Easy to get acceleration, velocity, and position	- Need numerical integration to get velocity using accelerometers, not accurate
	- Electric signals when biceps or leg muscles contract while infant crawls can be correlated with speed and direction of robot	- Direct movement of limbs is rewarded with mobility and encourage crawling	- Current classification error is still high - Not easily interfaced with robot software

Fig. 1 Preliminary design ideas

This paper is organized as follows. Section 2 provides a list of constraints and options in the design of this novel crawler on a mobile robot. Section 3 presents the detailed design of the crawler including considerations of system center-of-mass to ensure stability and safety of infants. Section 4 describes the single camera-marker system as the human-robot interface. The feasibility of our drive interface is shown by experiments conducted on two infants. Results are described in Sec. 5.

2 Preliminary Design

There are several design requirements of the robot-mounted crawler, which are as follows: (1) need for safety and child-friendliness, (2) intuitive drive interface between sensed motion of the hands and motion of the robot, (3) unrestricted movement of the limbs to allow opportunity for exercise of the arms and legs, and (4) interface with a commercial robot, in this case Pioneer 3-DX, equipped with position and speed sensing adapted within the design.

Pioneer 3-DX is a commercial robot from MobileRobots, Amherst, NH, and is a two-wheel differentially driven system with a third passive caster wheel. It is equipped with 16 sonar sensors on the periphery and ten bumper sensors. It has 23 kg payload limit and the dimensions are $44.5 \times 39.3 \times 23.7$ cm³ in length, width, and height, respectively. The driver and sensor interface must be integrated within the existing programming environment of the robot.

Figure 1 shows several choices to sense arm and leg movement of the infant and their interface with the rest of the mobility sys-

tem on the robot. Some of the relative advantages and disadvantages of these sensor/interface choices are also listed in the Table. These sensor choices include mice, strain gauge sensors, stereo camera, accelerometers, electromyography, and others.

Each option has its own limitation compared with our chosen solution, a camera-marker system. Using specifically designed markers, this system requires only one commercial web camera to detect the leg motion (Sec. 4). It is low cost and is compatible with the robot. Infants are allowed to move their legs freely. Upon review of currently available physical therapy devices to assist in crawling and the literature on physically challenged infant postures, we decided on an adjustable wedge on which the infant would rest prone while crawling. This wedge is seated on the Pioneer 3-DX robot.

3 Infant Crawler Seating and Support

The following fixtures were added to Pioneer 3-DX mobile base: (1) an extension base to improve its stability and (2) a support seating for the infant. These are described in more detail in this section.

3.1 Extension of the Robot Base. The robot base was extended to achieve a higher stability as the baby weight would shift on the robot. This extended base was constructed using planks of plywood in the form of triangular trusses and caster wheels. Two sets were made and placed on the left and right sides of the robot. This was done to avoid interference with ultrasonic sensors placed along the periphery of the robot. This changed the dimensions of the robot to 55.9×91.4 cm².

The support base was first placed on top of the Pioneer 3 robot. Then, trusses of the extension base were slid onto the top plate of the robot. Each truss also acts as a clamp to secure the extension base to the robot. Finally, the trusses are braced to each other via 22 in. long bolts. Figure 2 shows the two-step extensions of the base into the final assembly.

3.2 Infant Resting Support. The infant resting base was made from a 19×30 in². (48.26 cm \times 76.2 cm) piece of plywood, covered in polyurethane foam and fabric for safety and comfort as shown in Fig. 2. A wedge topped with foam was used to support the infant under the belly. To the front and back of the wedge is the driving interface consisting of a joystick for turning and a camera for detection of the leg motion. The stand for the wedge was made from T-slotted aluminum extrusions that allowed it to be adjustable in height and angle, as shown in Fig. 3.

3.3 Support Stability. In order to assess the stability of the support, anthropometric data of infants [12] were used to compute the distance of center of mass of the combined system from the ground.

Table 1 shows the mass distribution of the system to determine the system center-of-mass. Simple calculations show the overall height of the system is 52.1 cm (Fig. 4) and the total center-of-mass is 25.6 cm off the ground. This system distribution is considered safe because of the reinforcement by the extended base.

4 Human-Robot Interface

To control the robot, we use a single camera-marker system to track the leg motion and use this information to control the translational velocity of the robot. The rotational velocity is controlled by a joystick. This solution is low cost and can be easily implemented.

4.1 Single Camera-Marker System. We use ARTOOLKIT [13] as the camera-marker system. ARTOOLKIT is an open-source software library for building augmented reality (AR) applications. Even though it is built for AR, the program is easy to be adapted to detect the marker position. The features of ARTOOLKIT include the following:

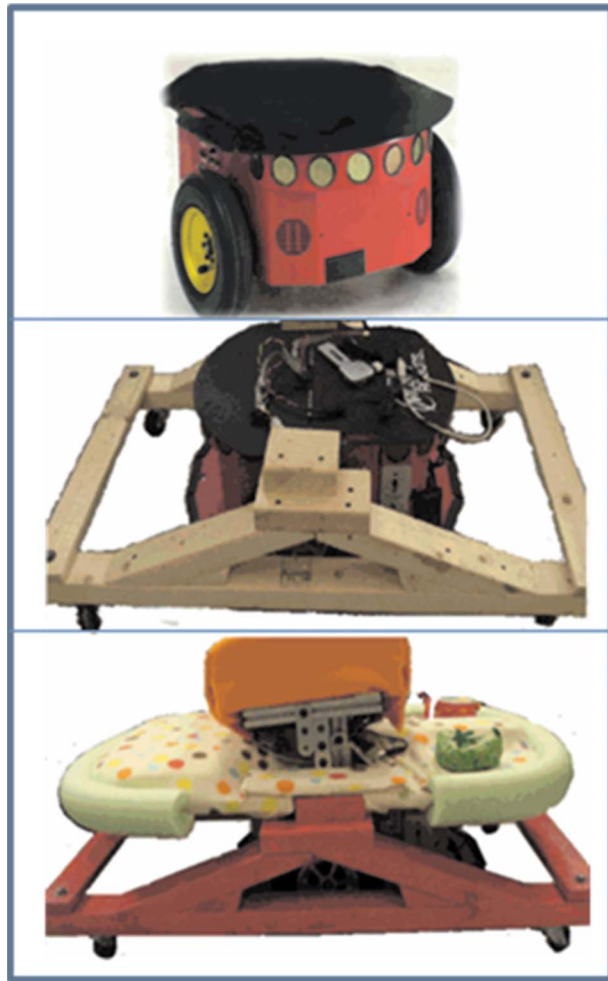


Fig. 2 Starting from the base of Pioneer 3-DX robot, an extension base was added to improve stability as an infant would lie prone on the robot. In addition, cushions were added to provide soft support.

1. requirement of only a single camera—while a high quality camera may result in better tracking, a web camera can give satisfactory measurements
2. measurement of six degree-of-freedom information using specifically designed marker (Fig. 5)
3. possibility to track multiple markers simultaneously and detect motion of both legs

We made an aluminum overhead cranelike support to mount the camera at the back of the robot. It detects leg motion using a marker on each leg (Fig. 3). The augmented reality software only tracks the position of a marker. These data are differentiated numerically to get the velocity of the marker. The forward velocity of the robot is set proportional to the velocity of child's legs, i.e., if the child moves the legs faster, the robot moves faster and reinforces this motor skill.

4.2 Turning Velocity. We use a commercial joystick (Logitech, Fremont, CA) to control the turning velocity ω of the robot. If the infant pushes the joystick handle to the left/right, the robot turns left/right with maximum turning velocity $\omega_{\max}=26$ sec. (Fig. 6).

4.3 Robot Programming Interface. Figure 7 shows the various modules of our crawler system. The camera sends frames to the onboard computer, which is responsible for programming high-level tasks, such as calculating marker velocity (through AR-

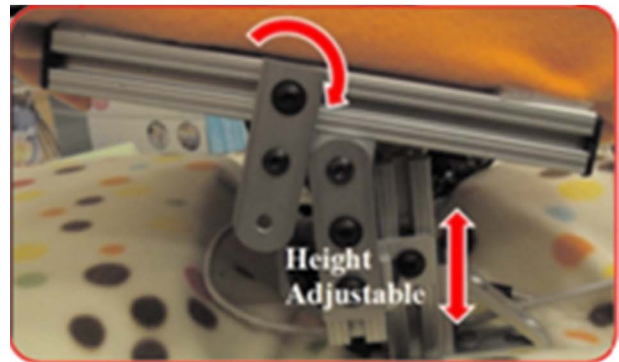


Fig. 3 Overview of the infant base with the foam wedge for supporting the infant, camera for capturing leg motion, and joystick for turning. The bottom panel shows a side view of the allowable adjustments.

Table 1 Mass distribution of system

	Mass (kg)	Distance ^a (cm)
Child (1 year)	11.2	38.1
Support base	4	25.4
Pioneer 3-DX	9	10.2

^aVertical distance from ground (point O).

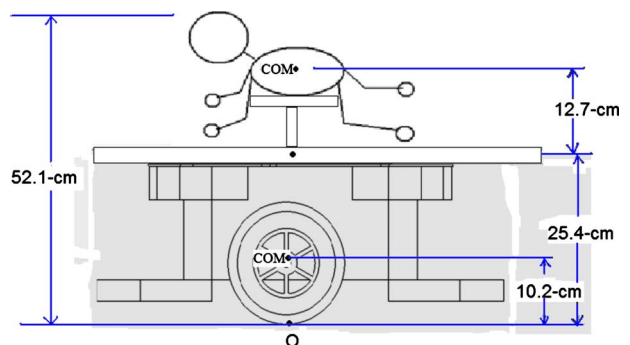


Fig. 4 Top view of the infant base with the foam wedge for supporting the infant and camera covered in colorful fabric to attract them. The bottom panel shows a side view of the allowable adjustments.



Fig. 5 A single camera detects six degree-of-freedom information of a marker

TOOLKIT), getting joystick input (through DIRECTX), and processing sonar measurements to avoid obstacles (currently not activated). The on-board computer then sends low-level commands to the robot's microcontroller, such as forward and turning velocity. The robot is also equipped with odometry sensors to record current position and orientation.

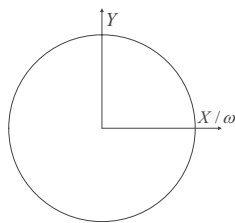


Fig. 6 Commercial joystick and mapping

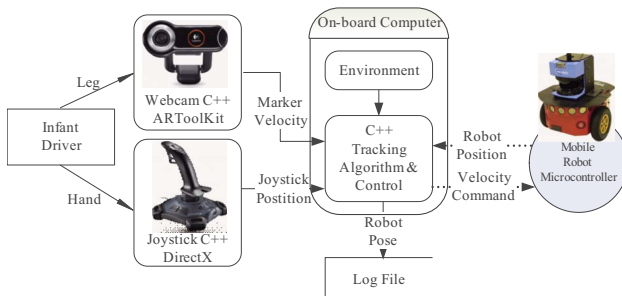


Fig. 7 A schematic of the robot drive interface

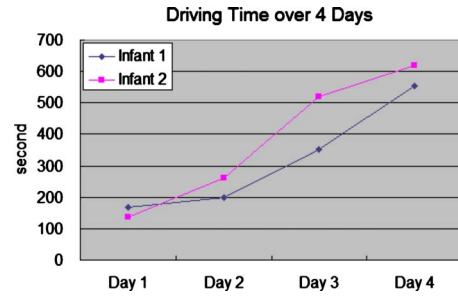


Fig. 8 Driving time for two infants over the 4 training days

5 System Feasibility

5.1 Methods. Experiments were conducted on two typically developing infants, 11 months old and 17 months old, to test the feasibility of the interface system and observe if it has any training effects. The first infant was still in the age of crawling. The second was able to stand or walk for short amounts of time but still crawled from time to time. Both infants were recruited from the Early Learning Center (ELC), University of Delaware. Their parents signed the consent form approved by the Institutional Review Board of the university.

Experiments were performed for 2 days a week and for 4 days altogether. During each day, the infants used the interface to drive as long as possible until they showed signs of fatigue or tried to get out of the safety straps. A caregiver encouraged the infants to move their legs and hands to move the robot. We predicted that infants would increase their tolerance for the mobile robot and move the robot for longer periods of time. We also predicted that their driving paths would become richer as infants adapt to the system.

5.2 Results.

1. Driving time (Fig. 8): Infant 1 drove for 167 s on the first day and for 555 s on the fourth day. Infant 2 drove for 136 s on the first day and 620 s on the fourth day. The driving time increased linearly with the number of driving days ($R^2 = 0.9707$ and 0.9634 , respectively), suggesting that driving time increased over the 4 days.
2. Path length (Figs. 9–11): Infant 1 drove for 2.34 m on the first day and to 10.64 m on the fourth day. Infant 2 drove for 3.41 m on the first day and to 13.86 m on the last day. Again, the results were almost linear with respect to the driving days ($R^2 = 0.9198$ and 0.9632 , respectively), suggesting that the path length increased significantly over the 4 days.
3. Path complexity (Fig. 11): The paths became richer with more complex maneuvers at the end of 4 days.

Both infants increased their driving time, path length, and path complexity over the four training days. However, based on our observations of the infants, infant 1 did not show purposeful driv-

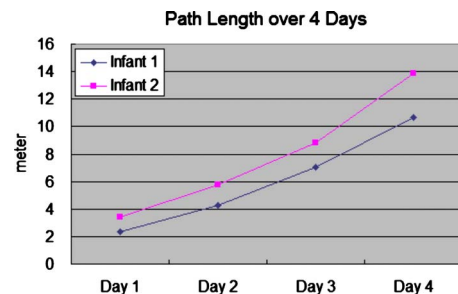


Fig. 9 Path length of two infants

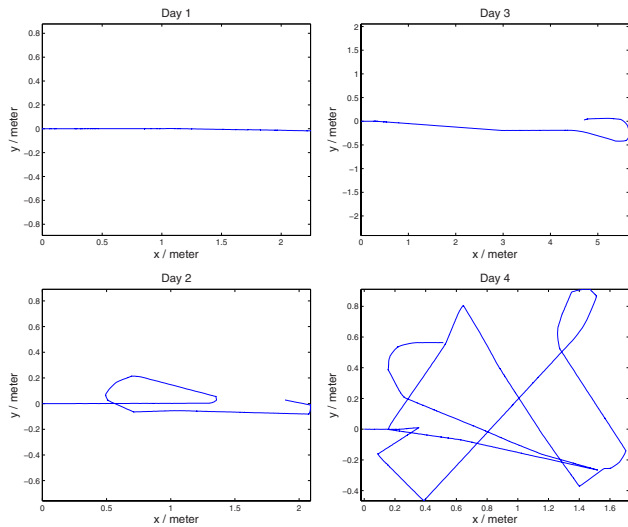


Fig. 10 Path traveled over 4 days of infant 1

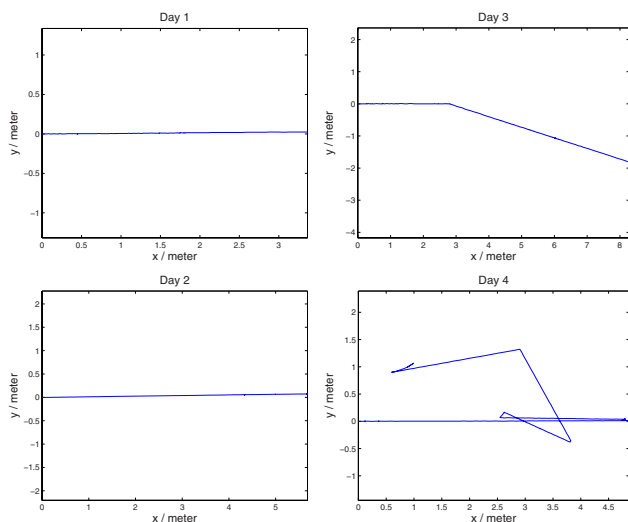


Fig. 11 Path traveled over 4 days of infant 2

ing to specific locations. However, by the end of fourth day, infant 2 did show signs of driving toward the caregiver.

6 Conclusions

The novel driving interface of the mobile robot, activated by leg motion, was successfully used by two infants to independently move around in the environment. We believe that the integration

of camera-marker system, as opposed to joysticks found in conventional powered wheelchairs, can be more accessible to infants as movements of the legs require less fine motor skills. The proposed drive interface simultaneously provides an opportunity for exercise while exploring the environment. The use of two markers can imitate crawling in the robot, encouraging infants to perform rhythmic patterns with their legs.

The feasibility of this interface was evaluated by experiments on two typically developing infants. Results showed that both infants increased their driving time, path length, and path complexity. More experiments are needed to show if infants can learn to purposefully drive the robot.

Acknowledgment

We would like to thank Steven Beard for his assistance in fabrication of the device at the machine shop. We acknowledge financial support from the National Institute of Health under Grant No. HD047468 and from the National Science Foundation under Grant No. NSF0745833.

References

- [1] Anderson, D. I., Campos, J. J., Anderson, D. E., Thomas, T. D., Witherington, D. C., Uchiyama, I., and Barbu-Roth, M. A., 2001, "The Flip Side of Perception-Action Coupling: Locomotor Experience and the Ontogeny of Visual-Postural Coupling," *Hum. Mov. Sci.*, **20**(4–5), pp. 461–487.
- [2] Uchiyama, I., Anderson, D. I., Campos, J. J., Witherington, D., Frankel, C. B., Lejeune, L., and Barbu-Roth, M., 2008, "Locomotor Experience Affects Self and Emotion," *Dev. Psychol.*, **44**(5), pp. 1225–1231.
- [3] Campos, J. J., Anderson, D. I., Barbu-Roth, M. A., Hubbard, E. M., Hertenstein, M. J., and Witherington, D., 2000, "Travel Broadens the Mind," *Infancy*, **1**(2), pp. 149–219.
- [4] Dancy, R. B., 2000, *You Are Your Child's First Teacher: What Parents Can Do With and for Their Children From Birth to Age Six*, Ten Speed, Berkeley, CA.
- [5] Proctor, D. C., and Proctor, J. M., 1989, "Creeper for Handicapped Children," U.S. Patent No. 4,796,903.
- [6] Williams, M. E., 2007, "Crawling Aid for Handicapped Infants," U.S. Patent No. 7,182,351.
- [7] Iams, J. F., Splane, R. L., Jr., and Drush, J. A., III, 1989, "Device Permitting a User to Simulate Crawling Motions to Improve Movement of Truncal Muscles and Spine," U.S. Patent No. 4,799,475.
- [8] Galloway, J. C., Ryu, J. C., and Agrawal, S. K., 2008, "Babies Driving Robots: Self-Generated Mobility in Very Young Infants," *Intel Serv Robotics*, Vol. 1, No. 2, Springer-Verlag, pp. 123–134.
- [9] Lynch, A., Ryu, J. C., Agrawal, S. K., and Galloway, J. C., 2009, "Power Mobility Training for a 7-Month-Old Infant With Spina Bifida," *Pediatr. Phys. Ther.*, **24**(4), pp. 362–368.
- [10] Ragonesi, C., Chen, X., Agrawal, S. K., and Galloway, J. C., 2010, "Power Mobility and Socialization in Preschool: A Case Report on a Child With Cerebral Palsy," *Pediatr. Phys. Ther.*, **22**(3), pp. 322–329.
- [11] Jones, M. A., McEwen, I. R., and Hansen, L., 2003, "Use of Power Mobility for a Young Child With Spinal Muscular Atrophy," *Phys. Ther.*, **83**(3), pp. 253–262.
- [12] McDowell, M. A., Fryar, C. D., Hirsch, R., and Ogden, C. L., 2005, "Anthropometric Reference Data for Children and Adults: U.S. Population, 1999–2002, Advance Data From Vital and Health Statistics," Report No. 361, National Center for Health Statistics, Hyattsville, MD.
- [13] ARTOOLKIT, <http://www.hitl.washington.edu/artoolkit/>