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Robotic Solutions in Pediatric Rehabilitation

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1. Introduction

The rehabilitation of pediatric patients involves unique constraints in comparison to adult rehabilitation. Therefore, the utilization of robotic technology in the rehabilitation of pediatric patients provides unique challenges. Research focusing on the application of robotic technology to pediatric cerebral palsy patients with spasticity is searching for flexible solutions that can address a wide range of patient capabilities. A variety of solutions are being investigated that place robotics in different roles in relation to the patient.

Cerebral palsy describes a group of neuro-muscular disorders that are caused by injury to the brain during the brain's developmental period. Cerebral palsy hinders motor skills and control of movement. According to the United Cerebral Palsy Research and Educational Facility, there are at least 550,000 persons in the United States with the disorder. Furthermore, there are approximately 9,750 new cases per year. Substance abuse and other factors also help increase the chances of the affliction (Matthews and Wilson, 1999; Styer-Acevedo, 1999).

Cerebral palsy affects the Basal Ganglia which is responsible for coordinating motion in the muscles. This affects all muscles of the body. The most noticeable muscles affected in children with cerebral palsy are the arm and leg muscles resulting in reduced motor skills, and the tongue which affecting speech and swallowing (Matthews and Wilson, 1999; Styer-Acevedo, 1999).

Cerebral palsy is usually diagnosed within the first two years after birth. Therefore, rehabilitative therapy for cerebral palsy patients may initiate shortly after birth. Although there are three main types of cerebral palsy: spastic, athetoid, and ataxic, the most common form of cerebral palsy is spastic cerebral palsy where high muscle tone constrains motion. Rehabilitation for pediatric cerebral palsy patients includes physical therapy, occupational therapy, and interventional medicine such as the injection of Botulinum-A Toxin paired with serial casting. Physical therapy early in the child's development prevents contractures and help to keep the muscles from becoming weakened or from deteriorating due to lack of use. Pediatric physical therapy differs from adult therapy in that patients often can not (or may not be willing to) follow direct instructions of a therapy routine thus therapy is incorporated in play. Furthermore, therapists must consider the natural progression of fine and gross motor skills in conjunction with developmental delays caused by cerebral palsy as a patient grows from infancy to adolescence.

2. Previous Work Related to Robotic Pediatric Rehabilitation

Robotics provide a reprogrammable flexible platform for manipulation and interaction with the robot's environment. The role of robotics in adult rehabilitation is well established. Robotic applications in adult rehabilitation have centered on the neuro-muscular difficulties

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experienced by stroke patients. Robotic devices to assist patients with their gait have been used to re-establish neuro-muscular pathways (Sawicki et al., 2006). Furthermore, robots have been developed that increase the bilateral range of motion of patients performing reach tasks (Burgar et al., 2000). In other related work, there is a variety of research investigating the use of gaming (Merians et al., 2002) or virtual reality to motivate adult patients in performing rehabilitative tasks. This research points to three capabilities that robotics can provide to pediatric patients with cerebral palsy: aiding the establishment of neuro-muscular pathways, extending range of motion, and providing patient motivation.

Previous pediatric devices have focused on the motivational capability of robots with children. Robots have been designed to target children with speech, learning, and physical disabilities (Plaisant et al., 2003). These robots mimic the actions of pediatric patients based on signals from armbands or leg bands. In addition, the robots used games and activities to encourage the children to continue their exercises.

The use of autonomous robots has been studied with autistic children (Michaud et al., 2003). It was hypothesized that “mobile robots can serve as an appropriate pedagogical tool to help children with PDD[autism] develop social skills because they are more predictable and less intimidating“ than an adult or therapist. The project consisted of six different robots, each with a unique look and set of abilities. Three of the prototype robots are shown in Fig. 1. It was found that positive reinforcement was an affective tool for the children to improve their skills. They explain; “having the robots behave in particular ways (like dancing, playing music, etc.) when the child responds correctly to requests made by the robot becomes an incentive for the child to continue playing with the robots”. The research found that the best and most effective robots appealed to the children’s visual sense, auditory sense, sense of touch, spatial perception and use of language. The use of lights, music, and short vocal messages excited the children and encouraged continued play. Unique problems were found in dealing with the pediatric population including possible damage to the robots and the danger of small parts as choking hazards with younger children.

In further research, a robot named ’’Roball”, shown in Fig. 2, was designed to develop the language, affective, motor, intellectual and social skills for children ages 12 to 24 months (Michaud et al., 2004). The robot has the ability to perform autonomous movement, sense, illuminate, and generate sound. A study of eight children investigated the development of each child’s motor skills, stimulation of intellectual skills, social interaction and language skills. This study focuses on the development of healthy children; however, the similar research could be compared and applied to children with disorders such as autism and various physical disabilities.

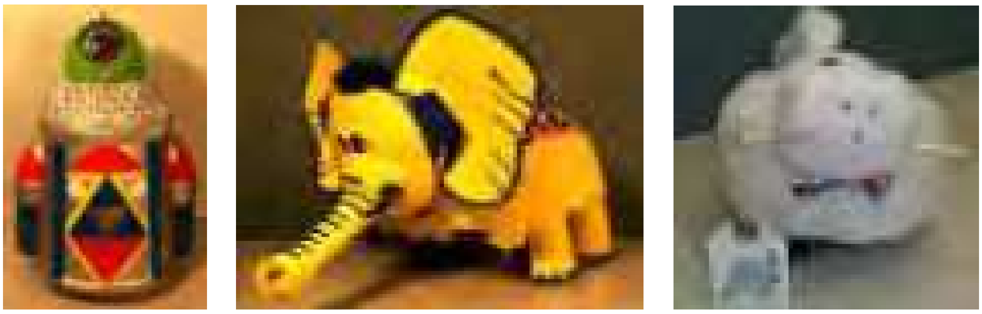

Fig. 1. Three Robots Used in Therapy for Autistic Children (Michaud et al., 2003).

Fig. 2. Prototype Roball and infant interacting with Roball (Michaud et al., 2004).

Pediatric related robotic systems that extend beyond motivational capability include the blocks assembly robot that provides the ability for blocks play children without the physical capability to manipulate blocks with their hands (Plaisant et. al., 2003). This system utilizes customized interfaces to provide children with a command structure that can be used to control a prismatic actuator. Some children with cerebral palsy may be a candidate for this type of robotic interaction. However, this is not directly a therapy related activity.

Although robotics has been successfully applied to rehabilitation and interaction with children, these systems have not been designed to meet the specific needs of children with cerebral palsy. Therefore, three different pediatric robotic therapy approaches are being investigated to take of advantage of reprogrammable platforms including an active rehabilitative boot, motivation robots, and an assistive robotic trainer.

3. An Active Rehabilitative Boot

An active rehabilitative boot is the application of a programmable platform to the stretching of the lower leg to maximize range of movement for children with spastic cerebral palsy. The most commonly occurring form of CP is spastic CP. Spastic refers to high muscle tone (tightness) which constrains motion. When both legs are affected by this condition it is classified as spastic diplegia. Children with spastic diplegia often will walk on their toes. This is caused by the contraction of the gastronemus muscle in the leg.

The most common rehabilitative method for spastic diplegia is interaction with a physical therapist to stretch the muscle in order to increase the range of motion for the patient’s gait. Physical therapy early in the child’s development prevents contractures and helps to keep the muscles from becoming weakened or from deteriorating due to lack of use.

A second rehabilitation method is an ankle foot orthosis. An ankle foot orthosis forces the ankle into a preferred position while the patient wears the device. This is often achieved through the use of fastening straps. It has been found that ankle–foot orthosis are beneficial to children with spastic diplegia during sit to stand transitions (Park et. al., 2004).

Another method of therapy is the use of Botulinum-A Toxin, also called Botox, paired with serial casting. The Botox safely and effectively reduce spasticity in specific muscle groups. Botox is administered by direct injection into a shortened muscle (for example a spastic calf muscle causing a tight heel cord) to temporarily weaken that muscle and allow it to stretch. The effects of Botox are not permanent; weakness typically lasts for a few months. In some cases, patients may require repeated injections to treat a shortened muscle. The Botox helps relax the muscles so the therapist can stretch the muscle group by securing the foot into position with a standard plaster or fiberglass cast. After approximately one week, the cast is removed, the ankle is stretched to the new limits, and a new cast is applied. This process is repeated throughout a period of four to six weeks. The serial casting procedure can be uncomfortable and modify the patient's behavior. A set of casts restricts the child's gait, which may lead young patients to revert to crawling. A set of serial casts for a 3 year old child was weighed and the average weight of a cast was 377g per foot. Cast materials can also lead to skin irritations causing the cast to be removed and the effective therapy window for the Botox injection may be wasted.

A new active orthotic boot is being constructed to assist in the rehabilitation of children with cerebral palsy that have spastic diplegia typically manifested by toe-walking. A new dynamic or active orthotic boot can assist in walking and gradual rehabilitation of the associated muscle group. The programmability of a microcontroller based device provides the boot with the flexibility to address the needs of different patients as well as different therapeutic applications.

In previous work, an active ankle foot orthoses to treat drop-foot has been devised (Blaya and Herr, 2004). The actuator modulates the stiffness of the low muscle tone ankle joint. Although this work proved the feasibility of an active orthotic boot, the actuator mounting on the back side of the calf would be problematic for pediatric patients. Furthermore, this previous boot required fast actuator response times in order to facilitate active ambulation of the patient. Our proposed boot for pediatric rehabilitation requires a much slower system response which enables the investigation of different actuation solutions. By incorporating new materials and technology, the boot can be more compact and lightweight resulting in increased patient comfort. Some important functional requirements of this new boot are the ability to adapt to changing rehabilitation requirements, the ability to store a history patient/boot interaction data for the therapist, and safety for daily use.

Thus, the rehabilitation of patients with spastic diplegia can benefit from the development of a new active orthotic boot that can provide a more flexible alternative to serial casts and also provide in home stretching therapy.

3.1 Rehabilitative Boot Design Concept

The active boot design targeted a thin wall boot similar to current orthoses with integrated actuators and feedback sensors to provide the proper stretch or set to a fixed "cast" position. Feedback on the patient is collected in terms of the foot angle and the pressure that the foot exerts against the boot and is monitored by a microcontroller. The microcontroller analyzes input signals and provides output voltage to the system actuators. The magnitude and duration of the system output can be tuned and customized for each patient. Based on the input of a pediatric physical therapists, an approximation of three times the patient's body weight provides an upper bound for the magnitude of force needed to be exerted on the patient's foot. The relationship of system components is depicted in Figure 3.

The boot design is based on existing DAFO configurations. Current manufacturing methods can be utilized to custom fit durable, lightweight plastic to the geometry of the foot and ankle. Figure 4 shows the final design and the original prototype. A thin film pressure sensor is located at the ball of the foot to detect the pressure resulting from the patient's tendency to walk on their toes. The sensor pads depicted in Figure 4 provide a stiffened package to improve the repeatability of the signal from thin film sensors. The objective of the pressure sensor is to determine whether the foot is bearing weight so that the brace flexibility can be increased to facilitate ambulation. An angle sensor is located at the hinge point of the boot. This can be used for dynamic feedback or verification that the boot is in a set "cast" position. Pediatric physical therapists have stated that +/- 10 degree range is typical for the target population.

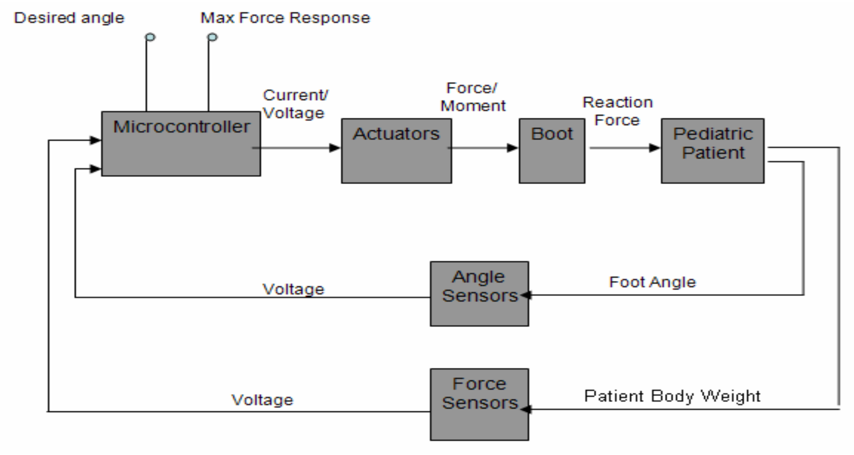

Fig. 3. System Block Diagram for a Pediatric Rehabilitative Boot.

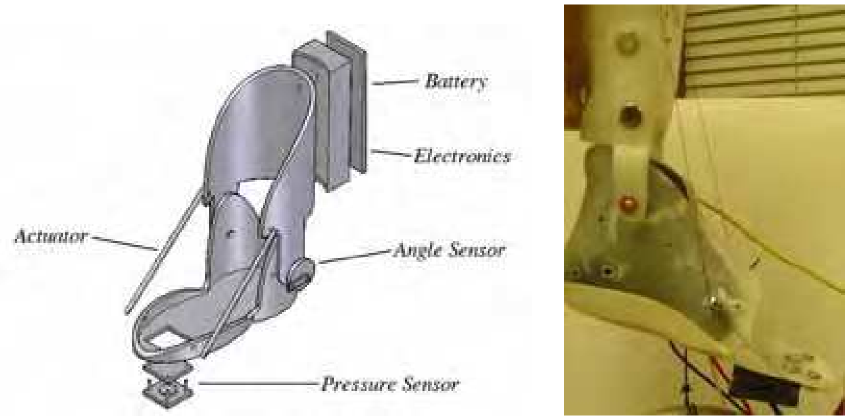

Fig. 4. A comparison of the rehabilitative boot design (a) and prototype (b).

Further development of a lightweight compact design integrates the actuators into the boot materials. Actuation can be achieved through contraction or bending. The microcontroller, interface circuitry, and battery are located on the back side of the boot to create an autonomous wearable device.

3.2 Prototype Rehabilitative Boot Design

System actuators must be able to move and stretch the leg muscles as part of a daily physical therapy routine. The concept of smart materials for use in orthotic and prosthetic devices has been investigated (Herr and Kornbluh, 2004) but not implemented. The use of electroactive polymer artificial muscles for assisting ambulation is discussed. Whereas the ambulatory system requires a high speed system response, the rehabilitation system benefits from a slow actuator response.

A smart material that meets the design requirements well is Shape Memory Alloys. Their unique pseudo-elastic and shape memory effects would provide the structure and motion needed in the therapy, along with the flexibility desired for safety. The heat being supplied to the wire is essentially the power that drives the molecular arrangement. This particular effect would be useful in the orthotic device as a way to change and set the desired distortion (length and angle). However, the pseudo-elastic properties are only exhibited when the alloy is composed of austenite phase and a load is applied. As the load is increased, the alloy transforms from austenite to martensite. The load strain is absorbed by the softer martensite, then as the load is reduced, the martensite transform back into austenite and returns to its original shape. In conjunction with the shape memory effect, the pseudo-elastic effect would be useful in the orthotic device as a general comfort and safety level assurance since the material would ideally give flexibility in its movement while still maintaining the needed shape. Some advantages the shape memory alloys have over other actuators include high power density (>1000 W/kg), large stress (>200 MPa), and large strain (~5%).

System sensors monitor the interaction between the patient and the boot. Force sensors are required to monitor that actuation forces are stretching the leg muscles while ensuring that the muscle is not torn. This is performed indirectly by measuring the force applied by the brace on the patient's foot. The sensor will be placed at the ball of the foot because the spasticity is often exhibited by the extension of the child's foot, as when the child is walking on his/her toes.

Since the boot is controllable it is possible to facilitate walking when the patient is ambulating by reducing the boot stiffness. In order to perform this function, the sensor must be able to differentiate when the patient is standing versus when the patient is sitting.

By placing sensors at the ball of the foot, the type of sensors that can be used are limited by the comfort of the user. Therefore a thin flexible sensor is required. Second, it should give consistent readings over a range of temperatures. As an approximation, the lowest temperature the sensor will experience would be during the winter months (0°C) and the highest temperature the sensor will experience would be during the summer months (45 °C). Finally, the sensor must give accurate measurements over the required range of forces, 0-108kg. Negative force measurements are not required since we are only concerned when pressure is being applied. The highest force will occur either when the patient is standing or when the brace is applying forces to the patient to stretch the leg muscles. The highest force will vary from patient to patient however an estimate of the force needed to stretch the leg muscles is no more than three times the body weight of the child. This gives a maximum force of 108 kg.

A thin film force sensitive resistor can meet the design requirements. This sensor was chosen because it has a thickness of 0.2 mm, high durability, and low cost. The ability of the sensor to detect small forces, indicating the patient is sitting, versus large forces, indicating the child is standing, will require the sensor to give a measurement within approximately 0 to 5 kg of the actual force. This can be achieved because the sensor has a repeatability of 2.5%, a hysteresis of 4.5%, a linearity of 5%, and a temperature error of 0.36% / °C.

The angle of the foot relative to the leg is an important measurement in the therapy. The objective is to stretch the leg so that the range in foot angle of the patient will match the range of a person who does not have spastic diplegia. Currently the angle of the foot is measured during visits to the therapist using a goniometer. The active boot will track the angle for active control of the boot. Furthermore, the availability of this data over time greatly enhances the physical therapist's insight into the ankle behavior. This information will give a more accurate picture of the patient's progress and can be used in future diagnosis.

An angle measurement sensor needs to be constrained to planar motions. Since the ankle joint can move with three degrees of freedom, the boot needs to measure a planar movement containing the calf and foot. In addition to this, the brace itself should be designed to limit rotation of the foot to only one axis. For this application, the range of angles is between -10^o to $+10^o$.

Finally, in order to meet the design objective for comfort, the sensor should be as small as possible and easily attached to the boot. Potentiometers provide a simple solution that meets the design objectives. This results in resistive elements for both the pressure sensor and the angle measurement sensor. The use of resistive elements provides for easy interface with a system microcontroller.

In order to provide a boot that can adapt to different patient requirements and support a wearable device, an embedded programmable controller is required. The system microcontroller has two modes: serial casting and therapeutic stretching. In the serial casting mode, a desired angle is maintained until the force sensor detects that the foot is supporting a load, such as walking. The boot then allows flexure of the angle by the patient to facilitate walking. Once, the boot comes to rest, the desired angle for stretching the calf muscles is restored. In home therapy mode, a therapy sequence can be initiated when the patient is at rest. The boot is slowly cycled through a stretching exercise that has been set by the physical therapist. The safety functions of the boot system require a fast monitoring rate, so there will be no muscle damage. However, a high speed microcontroller is not required. The Parallax BS2-IC microcontroller was selected for development of a prototype rehabilitation boot based on familiarity with the device, no need for numerous I/O pins, cost and ease of programming.

3.3 Rehabilitative Boot Conclusions

Bench testing of the boot proved that the proposed actuator is sufficient for the stretching task. However, the prototype achieved a range of motion of 8-10 degrees short of the device goal of +/- 10 degrees. This discrepancy can be accounted for by changes to the actuator and boot geometry. Furthermore, heat generated by the actuator presents safety concerns which are being addressed.

Overall, it can be concluded that the concept of a wearable active rehabilitative boot is feasible. Continuation of the project will model and test candidate materials with and without embedded sensors.

4. Physical Therapy Robot Study

As stated earlier, there have been instances of motivational robots in physical therapy. However, it does not appear that the design of robot activities has been designed as a tool for the pediatric physical therapist. Therfore, motivational robot sessions were investigated by reprogramming commercially available robots to perform some standard therapy routines and instructing children to mimic the robots actions. These robots were designed for children who suffer from Cerebral Palsy. It should be noted that these children tend to have more physical difficulties. Everyday activities such as walking, crawling, or stretching are a struggle for these children. A child's physical impairments can lead to a low perception of self-efficacy and self-competence due to having difficulties engaging in play activities (Miller and Reid, 2003). To address these issues, proposed therapy routines for CP patients will focus on walking, stretching, and positive reinforcement for motivation.

After preliminary interviews with pediatric physical therapists, it was revealed that therapists often have difficulty keeping a child's attention during physical therapy sessions. Furthermore, they often have difficulty persuading the child to perform his or her required exercises. The goal of this project is to fully create, program, and implement therapy routines using the Sony AIBO robotic dog (model ERS-220) focused on the needs of Cerebral Palsy and Autism patients in the age range of 3 to 12. More specifically, the robotic dog will be used to improve children's motor skills and social interactions during physical therapy sessions.

The group has thoroughly investigated several pediatric disorders and found that both Autism and Cerebral Palsy (CP) will benefit most from AIBO's capabilities. Therapists and professionals were consulted to aid in developing several proposal routines that can be programmed into AIBO and implemented during therapy sessions. These proposals consist of motivational games, stretches, exercises, and social activities designed to enhance the current sessions. The Sony AIBO, a robotic dog, was chosen as prototype due to its vast capabilities, intricate programmability, and its highly sophisticated components. The autonomous robot is fully programmable and responds to its surroundings. Its performance is enhanced with colorful LEDs and the ability to play music and sound clips.

A user friendly interface will ensure ease of use for the therapist and parents. Overall, the project hopes to aid children suffering from these diseases by improving their physical, cognitive, and social skills, all while enhancing their overall well-being.

4.1 Physical Therapy Robot Activity Design Concept

The physical therapist centered design methodology was implemented using seven design criteria. These criteria required the final designs to: 1) be within AIBO's physical capabilities, 2)correspond with the desired age group, 3) address a pertinent or common physical, cognitive, or emotional problem, 4) have a high predicted effectiveness, 5) be relatively simple to program, 6) pose no risk of harm to the child, and 7) be easy to evaluate the effectiveness. These criteria wereapplied to activities targeting two distinct populations of children: children with autism and children with cerebral palsy. The proposed therapy routines for autistic children focus on speech, interaction, and play. The proposed therapy routines for cerebral palsy patients will focus on walking, stretching, and positive reinforcement for motivation.

Under the guidance of professional therapists, several Autism routines have been developed and each evaluated based on the seven feasibility criteria described above. One proposed activity is a voice activation game in which the child can command the dog to perform a certain action such as "sit," "stand," "move forward," "walk right," etc. Children with Autism typically have trouble asking questions or with speech in general. This will encourage the child to not only speak, but also ask a question or make a command. The child will be further motivated to play with AIBO when he or she sees AIBO successfully perform the desired action.

Another proposed activity is a game that involves throwing and kicking AIBO's pink ball (a special ball that comes with the robot). The child will gently throw or kick the ball to AIBO and the robot will locate the ball and kick it back to the child. This activity could involve more than one child to further encourage social interaction for the Autistic child.

The last activity is a sensory exercise that utilizes AIBO's pressure sensors. Autistic children often cannot distinguish between touching something hard and touching it lightly. This activity begins with the therapist (or adult) telling the child to touch one of AIBO's buttons "hard." If the child touches lightly and lifts his or her finger, AIBO will shake his head "no" and the child can try again. If the child succeeds, AIBO performs a celebration dance.

Several routines for cerebral palsy patients were developed. The first routine is a game that will be used to motivate children to walk. Most cerebral palsy patients have trouble walking and many patients do not have any motivation or desire to try to walk. To address this, AIBO can be programmed to walk in front of the child a set distance (approximately 1 meter). AIBO will then turn around and face the child. The robot will use its distance sensor to determine whether the child has walked closer (within ¾ of a meter from AIBO). Next, AIBO will complete a celebration dance if the child succeeds or sit and wait until the child does. This process can be repeated the desired number of times as specified by the therapist or parent.

To aid the cerebral palsy patient in his or her stretches, a "Follow the Leader" set of activities is proposed. This set of activities will involve AIBO performing a stretch and the child mimicking the robot for the desired number of repetitions as specified by the therapist. One example stretch is referred to as the "Airplane," which requires the child to lie on his or her stomach. The child will then lift all four limbs into the air. This stretches and works the abdominal muscles and is often recommended for cerebral palsy patients (see Figures 5 and 6). Other proposed mimicking activities include arm extensions, balancing, hamstring curls, leg extensions, sitting up tall, pushups, rolling over, and stair climbing.

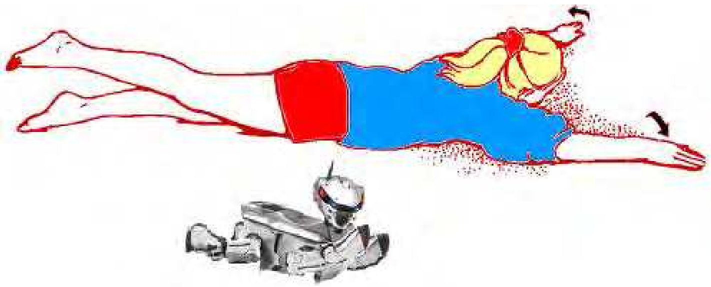

Fig. 5. A physical therapy document showing the airplane stretch along with the robot implementation.

An important aspect of the robotic therapy tool is ease of use for the therapist. A colorful user interface with detailed directions and an instructional computer program ensure that the therapist can perform the desired routine without delaying a therapy session (see Figure 7). Each routine can be accessed by pressing a combination of colored buttons on AIBO's back side. For instance, to instruct AIBO to perform the leg extension activity, the user must simply push the blue button and then the red button.

Evaluations of the project will be based on each child's level of motivation to participate in the activity, overall emotional effect that the activity has on the child, and the child's performance and overall improvement when completing a routine.

Fig. 6. Children Performing Airplane Stretch with AIBO.

Fig. 7. Color code routine selection designed for therapist use.

4.2 Physical Therapy Robot Testing

After selecting various routines to be implemented, several programming designs were created for each routine. Smooth, human-like movements were desirable for each routine. When determining the best program design, robot positioning and stability were considered. This initial testing ensured that AIBO would remain stable throughout the routines and would look life-like to the users.

Pilot testing was conducted for the cerebral palsy routines during therapy sessions at a preschool, which is designed for children ages three to five with various developmental delays. Half of the test population at the preschool were typically developed. Testing was conducted by a physical therapist familiar with the project who also evaluating the robotic tool. Five groups were tested for 10-15 minute sessions. The sessions were video taped. A second set of sessions was performed a month after the first.

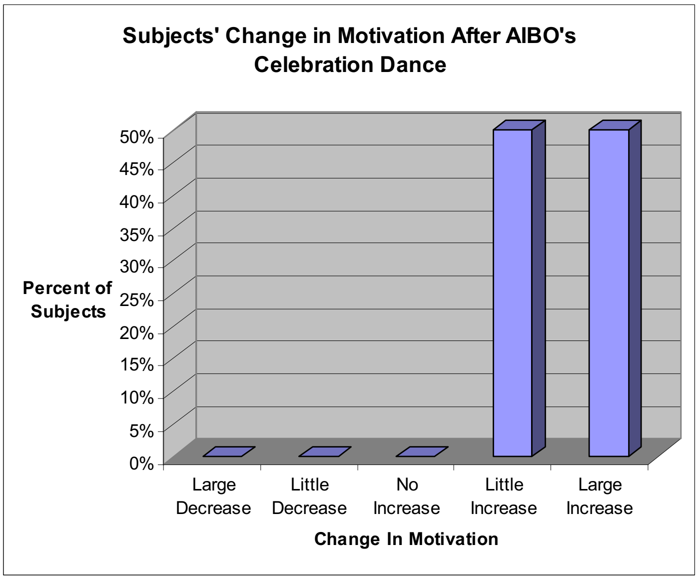

Fig. 8. Pilot study results regarding motivation.

Therapist evaluation of the tool was collected with a survey. Furthermore, video tape of the sessions were reviewed for visual cues. Results presented in Figure 8 and Figure 9 include a increased willingness to imitate body positions and a high level of enthusiasm for all participants. Most participants correctly mimicked the robot movements. In exercises that separately moved limbs on the right and left, some participants moved the wrong limb. Participants that were exposed to the robot therapy a second time did not lose motivation or enthusiasm with the second exposure.

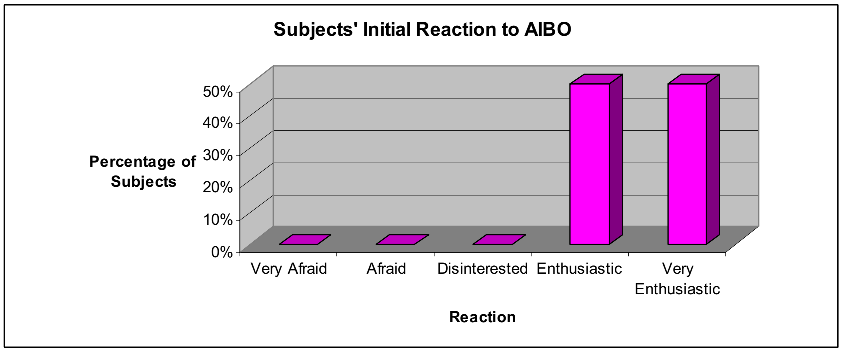

Fig. 9. Pilot study results regarding enthusiasm.

3.3 Physical Therapy Robot Conclusions

Programming a robot to aid pediatric physical therapists provides an effective tool for the therapist. The programmable platform can be used to provide an alternate method of performing existing therapy tasks. A robotic solution provides a tool that can be applied to a wide range of patients with little set up time. Further studies need to be conducted in order to test the long term effects in therapy.

4. Final Conclusions

The results of the two studies provide evidence that there are wide ranging opportunities in the area of pediatric rehabilitation for the application of robotic platforms. Two very different platforms were presented addressing two distint therapy outcomes. In both cases, the inclusion of rehabilitation professionals was essential in the deign of the device or activity. System design considerations need to be based on direct therapy goals and robotic systems need to be evaluated on medical outcomes.

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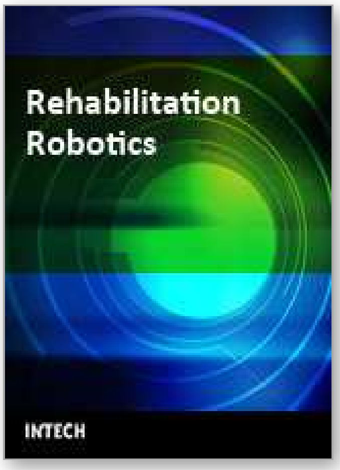

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The coupling of several areas of the medical field with recent advances in robotic systems has seen a paradigm shift in our approach to selected sectors of medical care, especially over the last decade. Rehabilitation medicine is one such area. The development of advanced robotic systems has ushered with it an exponential number of trials and experiments aimed at optimising restoration of quality of life to those who are physically debilitated. Despite these developments, there remains a paucity in the presentation of these advances in the form of a comprehensive tool. This book was written to present the most recent advances in rehabilitation robotics known to date from the perspective of some of the leading experts in the field and presents an interesting array of developments put into 33 comprehensive chapters. The chapters are presented in a way that the reader will get a seamless impression of the current concepts of optimal modes of both experimental and ap- plicable roles of robotic devices.

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