The Humanoid Rehabilitation Project

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ABSTRACT
Pediatric rehabilitation is a field of medicine which can be fraught with challenges specific to children. Physical therapy, concerned with rehabilitation of gross motor skills, can be complicated further by a range of physical or social developmental issues. Therapy can also be limited by the inability to maximize continuity of care for patients in between sessions. Mitigating these issues through the creation of a robotic platform is the primary focus of the Humanoid Rehabilitation Project. In particular, the robot will be capable of alleviating these issues by 1) serving as a customizable and engaging visual model which can demonstrate a particular rehabilitation exercise or movement and 2) by behaving as a surrogate between the therapist and the child or the parents and the child. By acting as both a visual model and a surrogate for interaction, discomfort and social pressure felt by the child during a therapy session with adults can be reduced while a useful technique or exercise can be introduced and taught more effectively. In order to accomplish these objectives, the Humanoid Rehabilitation Project developed a unique, replicable robot named HCTeR, short for Humanoid Companion Technology for Rehabilitation, composed of a 3D printed, FDM structure, widely available off-the-shelf electronic components, and relying on the Arduino family of microcontrollers.

Keywords
Robotics, Humanoid Legs, Bipedal Platform, Rehabilitation, Microcontroller, Servo Motors, Physical Therapy.

1. INTRODUCTION

1.1 Problem Statement
Physical therapy is a rehabilitory form of physical medicine which involves the strengthening and development of gross motor functions in individuals with impairment caused by disease, injury, or cognitive disabilities [1]. Physical therapy can be a difficult process for anyone. Whether a person is attempting to regain a function or learn a new one, the amount of lasting, desirable improvement can be greatly affected by how receptive a patient is to the required therapy. Pediatric rehabilitation brings with it new issues. However, when the patient is a child with other developmental issues, teaching and guiding a successful round of therapy can become a much more robust problem [2]. Specifically, the spectrum of autism disorders, among others, causes pediatric patients to experience debilitating stress or complete closure to interaction in social settings. This can often make physical therapy much more difficult if not impossible.

1.2 Motivation
This robot is being designed initially as a tool to reach children with social or emotional developmental issues who have trouble or are not responsive to traditional forms of physical therapy. It is intended to be an aid tool for physical therapists and parents caring for these developmentally impaired children. By utilizing a robot to demonstrate an exercise or motion to a socially or emotionally handicapped child, the human interaction element can be minimized. In this way, emotional or mental stress can be reduced for the child patient and the learning process may be improved. Because the functionality sought lies in bridging the communication gap with impaired children, a design focus must be placed on creating a robot which is aesthetically pleasing and visually captivating to these children. In addition, the robot, which will mirror the proportions and stature of the patient, may also be used by the child and parents at home to improve the continuity of therapy in between sessions in addition to its therapist surrogate function.

Currently, an open source project called the Poppy Project has sought to develop a database of accessible information for creation of robots. In particular, a robot created to study the biomechanics of biped motion with a focus on how morphology can affect cognition is being used as a point of reference [3]. Because of the costs associated with the Poppy Project and other similar humanoid robotic platforms at thousands of dollars per robot, another significant motivation for this design is producing a unit at a lower price point.

1.3 Literature Survey

1.3.1 Humanoid Robots
As robots become increasingly present in society, the importance of understanding their origins is magnified. Humanoid robots were first used in research for the purpose of modeling how the human body rudimentary functions. Eventually, these robots gained certain characteristics such as motion and problem solving skills limited by their programming. By utilizing different kinds of mechatronic systems, humanoid robots can be designed to perform tasks that would otherwise seem limited to humans. Motors and servos can produce a flexible output in terms of speed, power, and precision that would be limited only by the characteristics of the components. As technology progresses, so do the abilities of these robots. According to Smashing Robotics, the advancement of A.I.

technologies will allow humanoid robotic systems to display "intelligence…surpass[ing] human intelligence by 2030." These robots are becoming less restricted to laboratory environments and are slowly growing into a part of society whether it is assisting humans, performing surveillance and other military functions, in prosthetic applications, and many other areas of study. Generally, the cost to produce almost any humanoid robot makes it inaccessible for many, as costs can reach $5000 for a unit [4].

1.3.2 Pediatric Rehabilitation

Rehabilitation for children differs from adults in a few ways. One is that pending their age, they may be learning an activity or motor skill for the first time. This means that they don't already know how to perform a function and that they may not be motivated to learn since they've gotten along fine without that functionality thus far. Children also have different body proportions (all children do, but some conditions such as Down syndrome can exaggerate the differences), so you can't just take adult items and do a simple scale. Children also tend to be visual learners, have shorter attention spans and may be shy or avoid adults, particularly strangers. Developmental delays such as autism, which is a condition more prevalent and understood today than ever before, result in children having even greater tendencies towards these behaviors.

Doctors often recommend physical therapy (PT) for children who suffer from certain injuries or who have motor problems associated with certain other conditions. PT might be needed any time a problem with movement limits someone's daily activities. Whether the disability is physical, an illness, or a disease, physical therapists work with the kids in order to decrease pain or to discourage undesired tendencies to help children return to their (or gain) daily activities. To accomplish this, therapists perform different exercises that focus on helping children regain strength and range of motion while at the same time showing families how to prevent future injuries [2].

1.3.3 Poppy Project

The Poppy Project is an open-source platform for the creation, use and sharing of interactive 3D printed robots. It gathered an interdisciplinary community of beginners and experts, scientists, educators, developers and artists. They all share a vision: robots are powerful tools for learning and creativity and collaborate to improve the project. They develop new robotic behaviors, create pedagogical content, design artistic performances, improve the software or even create new robots [3].

The Poppy project evolved through a community that developed an easy to build and customizable robot that is promoted as an open-source project. In this way, anyone can use it and further develop its hardware as well as its software. A forum has been established to make all this information accessible to the public. Since Poppy is an open source platform, all sources of the Poppy Project (software and hardware) are available.

1.3.4 Ottobot

The Ottobot is another open source project tasked to interact with kids to improve their social engagement issues. This robot is a small toy that interacts with the environment as well as other Ottobots. While a much smaller project than Poppy, Ottobot shows how 3D printing can be leveraged to create affordable robots which produce a positive social impact. Because this small robot appeals to children trhough movement, dance, and sound, it is inclusively designed to encourage social interactions and emotional engagement in youth with autism and other special needs. It is intended to be a surrogate for practice with emotional expression or communication. This robot also features a control app on smartphones that changes its functions very easily without having to restart its coding process. This makes this toy-like robot a much more versatile tool for social engagement [5].

2. PROJECT FORMULATION

In general, this project was developed as a platform for implementing robotics to supplement pediatric physical rehabilitation with an emphasis on reaching socially or cognitively impaired patients. Physical therapy involves the strengthening and development of gross motor functions and is often a very burdensome and difficult process which can be further complicated by emotional or learning disabilities. Initially, this application of technology addresses issues regarding interfacing therapy with socially less-responsive children and it will also allow for improved continuity of care. This, however, is not to be taken as a limiting condition for application and use. Because of the open source nature of the work, it can be expanded to possibly include new, more accessible programming tools or increased functionality such as remote control by a therapist, allowing for a more flexible "telemedicine" approach to physical therapy which could reduce the cost of care.

2.1 Objectives

The motive of this design is to contribute to society by improving the relationship between a therapist and the child that is undergoing treatment. By creating a robot that serves as an inexpensive surrogate and mediator during pediatric rehabilitation, the team hopes to help patients by providing a new treatment tool and improve results when compared to or used in addition to tools that have been used in the past.

Two main functions that have been selected as design objectives for this robot. The first function of the humanoid robot will be to be capable of serving as a visual model that children may observe and learn from through mimicry. In this way, it will become possible for a therapist to demonstrate a certain movement or exercise to a child through the robot. The second function chosen was for the robot to serve as a social intermediary between the physical therapist and the child patient. Among children who have cognitive disabilities, a major issue in providing any medical treatment often arises from the child's resistance to social interaction with a provider. By allowing for the introduction of interesting stimuli (i.e. lights and sound) and downplaying the human element of receiving physical therapy, the Humanoid Rehabilitation Project will aid in bridging this gap. This combination of functions and priorities will allow a therapist the possibility of more easily demonstrating to a child, how to perform certain activities or exercises.

A secondary yet significant benefit can also be yielded from the Humanoid Rehabilitation Project effort. Because the nature of the project is modular and open source, the project can also be used to improve continuity of treatment. The platform, in concept, may be used and practiced with at home by the child with parental supervision or with therapist supervision via a telemedicine functionality which could be incorporated at a later time. By creating a robot which places an emphasis on hands-on interaction for the patient, the child will interact through different exercises as well as learn through modeling from the robot.

2.2 Design Specification

With the intention of creating a more accessible robotic platform, one of our goals is to reduce the overall price while keeping the quality of our final project in comparison to similar humanoid platforms. With the Poppy Project being the most similar humanoid robot surveyed and using that unit's cost as a reference, we hope to reduce the price by at least 50% while maintaining a unit capable of still performing the required functions. In order to accomplish this, a competitive price analysis was performed concluding that the servo motors are the most expensive component in most humanoid robotic devices. For this reason, servo selection became paramount. Replacing the more expensive units with cheaper servos that are still capable of achieving the required degree of performance may provide a means of reducing the final price of construction significantly. In an attempt to lower the final cost further, the team agreed on including component sourcing information rather than providing any components via the Humanoid Rehabilitation Project itself, unlike other open source projects which may profit from selling components. Therefore, all 3D printable components will be accessible and ready to print using a suggested 3D printer, filament, and a listing of trusted distributors for other critical off-the-shelf components.

2.3 Addressing Global Design

Maintaining positive global awareness is a key aspect of any ethical design procedure. Evaluating the resulting consequences and implications a project may have on different people is paramount for producing an end design that accomplishes the task. Accessibility and inclusiveness are cornerstones of solutions that work.

In this design procedure, the target audience is pediatric physical therapy patients with varying disabilities, their families, and the pediatric physical therapists who treat them. This group requires that many careful considerations be made to maintain a high degree of sensitivity. In order to create a solution which is highly accessible and inclusive, three primary factors are being considered in the design which will allow this goal to be achieved.

First, designing with the intent to produce a product with the lowest possible cost will allow this technology to be available to people coming from a wide range of socioeconomic backgrounds. Patients in countries with lower standards of living will be more likely to benefit from this technology with lowered cost. By placing an emphasis on informed component selection for things like microcontrollers and servos, and relying on 3D printing for the bulk of the manufacturing requirements, it will be possible to create a functioning humanoid robot at a lower price point than previously available.

Another major consideration will be focused around continuity of care. Physical therapy typically occurs at a dedicated location such as a clinic or office, or in another appropriate setting such as a home visit. Both of these scenarios involve a physical therapist's direct contact with a patient in order to produce the desired results. However, conducting the optimum number of these face-to-face sessions may be limited by insurance coverage, local therapist availability, or other cost prohibiting factors. By implementing this robotic tool, a family may be able to increase the frequency of therapy without increasing the associated costs of more clinic visits and more hours with a therapist. As a limited surrogate, the robot will allow a family to take more ownership of the therapy process and fill the treatment gaps.

The final consideration being made regards how individual, unique cases may be addressed. By leaving our design process completely transparent and open source, this robot can be modified and customized by someone closer to a particular case in order to produce the optimum amount of benefit. For example, the programming could be altered to allow the robot to interact in a different language or exhibit disproportionate strength in one limb versus another in order to better approximate the individual patient. Also, because the robot structure will be entirely 3D printable, it will be possible to adjust the physical dimensions and scale of the model in order to create a high degree of similitude between the patient and robot. However the model or program is modified, flexibility is key in order to reach the greatest number of patients.

2.4 Constraints and Other Considerations

In this project, the biggest limiting factor was time. This was a very complex design, and the programing took the longest portion of the design process. However, since this is an open source project, this limiting factor for functionality is mainly based on what an end users' individual programming knowledge allows. Through the development of one rudimentary programmed procedure, the platform's functions may begin to be understood and improved upon by end users and any continuing design efforts.

3. DESIGN ALTERNATIVES

In order to improve the quality of our final project, we decided to divide our design process into two stages. The first stage consisted of developing a prototype to provide a reference point regarding maintaining the most accessible budget and allowing for some initial testing and analysis to be performed. The prototype used economical, but less capable servos, and had a 3D printable structure with an emphasis on reducing total filament usage. A kinematic analysis was performed using the prototype to determine the range of possible motion and to ensure anatomically realistic movements. Finally, testing of possible additional features such as Bluetooth remote control, MP3 playback, eye emotion simulation, and wi-fi connectivity could also be performed.

The second stage involved creating a new platform which modified and improved the original prototype. It was of a larger size, but retained the same degrees of motion. This way, the prototype more closely models a child and can be more capable in general. For this stage, we focused on the programming and hardware capabilities. By keeping all the functional features, but implementing more effective servos and incorporating other components directly aimed at appealing to a child, the design provides a better model for the patient undergoing treatment.

3.1 Design Alternate 1

The first step in implementing this prototype was the components selection. Since only a small scale of the prototype was to be designed for this stage, the use of economical servos was justified. This small scale prototype serves as a learning guide into how the different limbs attached to the humanoid brought movement. Based on these dimensions of the chosen components, a humanoid was designed with 3D printable limbs to simulate the optimal movement of the joints.

At this prototyping point, and because of its design intent in being appealing to children, the group decided to name the humanoid robotic platform HCTeR, pronounced Hector. HCTeR is short for Humanoid Companion Technology for Rehabilitation.

3.1.1 Components

3.1.1.1 Arduino Mega

The Mega 2560 is a microcontroller board based on the ATmega2560. It has 54 digital input/output pins (of which 15 can be used as PWM outputs), 16 analog inputs, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button [6]. Also, the Arduino Mega is capable of controlling several servos simultaneously as well as many other components. In addition, there are many forums and websites full of useful information of how to use the Arduino that will help us during the project design. Lastly, since Arduino is an open source platform, the price of the Arduino is relatively low compare to other microcontrollers. For all these features, the Arduino Mega was chosen as the microcontroller.

3.1.1.2 SG90 Servo Motor

To pick the correct servo motor for this prototype stage, power was not a deciding factor. Since this prototype was only going to be a small scale design, we turned to the economical aspect of the servos. This is why the SG90 servo motor was chosen.

This servo provided us with an operating voltage of 5V, an operating speed of 0.1s per 60 degrees, and a stall torque of 1.8 Kg*cm, all of this while having a total weight of 9g. This servo is very limiting in that it has only one input and, unlike other more expensive servos, does not provide feedback [7].

3.1.2 CAD Model

This design features a humanoid torso, as well as the arms with five servos that provide one degree of freedom each. This is the structural design of prototype HCTeR. This design is 54cm tall, and has a length of 15.25 cm shoulder to shoulder. This prototype also featured stationary eyes to give us an idea of what the final design would have. Stage two will feature eye components that, once programmed, will simulate emotion through different facial expressions, making the robot appealing, accessible, and unintimidating.

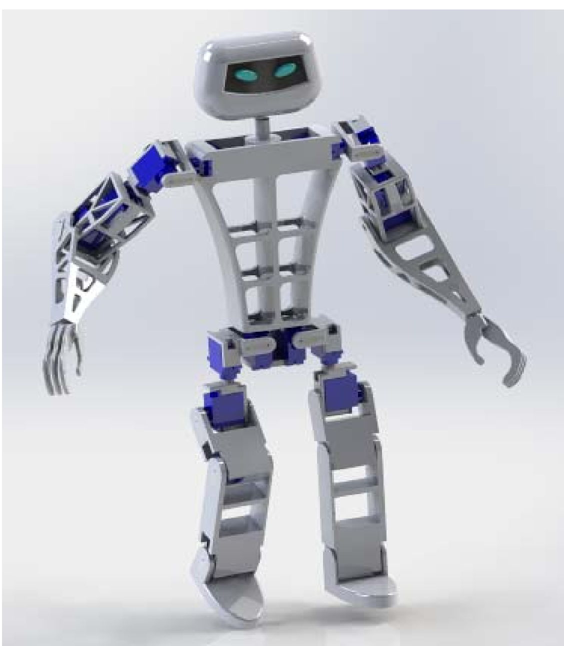

Figure 1. First Prototype of HCTeR

3.2 Design Alternate 2

After careful consideration, the group decided that the new design had to be done from scratch introducing only the design ideas that the group wanted to reuse. With this in mind, it was decided to remove one degree of freedom in the arm; the servo omitted from this design created a rotational motion of the arm which the group believed would complicate the design in this stage. This motion can still be added to future prototypes.

Another consideration was the redesign of the legs. The legs did not work as expected. However, a successful analysis of the degrees of freedom provided by the legs was what the group hoped to achieve in the first prototype. For this design the legs will remained at ten degrees of freedom.

3.2.1 Components

Because of the many alterations between stage one and two, some of the components were changed. Design two featured an increased height and weight which meant that stronger servo motors, as well as a higher current output, was needed. The Arduino Mega remained as the chosen microcontroller. This microcontroller successfully controlled the new servo motors. However, a different power supply was used to power these since the Arduino is only capable of powering up to two servos at a time. Also, this design featured the ability to add new components such as Bluetooth and wi-fi connectivity shields for Arduino.

An additional servo was introduced in the hip to create a rotational movement on a plane parallel to the floor. This facilitates walking and allows a turning movement of the torso for different therapy exercises. The complete design features 18 degree of freedom of movement, including the neck movement.

3.2.1.1 MG996r Servo Motor

For the final design, it was fundamental to increase the total functionality of the servo motors, since the design was of a much larger scale. TowerPro's MG996r servo motor possesses a torque of 11 Kg*cm at 6 V, a stall torque of 15 Kg N*cm, and a total weight of 55g. [8]

3.2.1.2 LCD Display Module

The eye components consist of two LCD display modules. These are 3.3V, 0.96 inch screens that will work as a display for each eye as shown in the figure below. The LCD display module is of utmost importance since it helps display HCTeR's emotions through its eyes. For cases where a child might not understand emotions as well, the expressions shown by HCTeR can be altered to prevent frightening children.

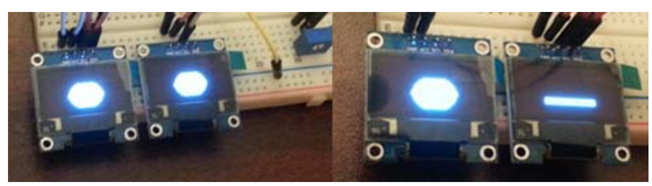

Figure 2. Eye expressions. This figure displays two of the many possible emotions that can be coded into the display

3.2.2 CAD Model

The CAD model of the final design features a bigger and friendlier looking platform. Although this model borrows greatly from its previous stage, the group decided that changing the total degrees of freedom of the previous design to 18 (5 in each leg, 3 in each arm, 1 on the hip, and 1 on the neck) will still allow for all the essential movements. This design also has LCD screens as eyes, and careful placing of wiring and servos to prevent harmful situations. This design is shown in Figure 3.

Figure 3. HCTeR stage 2

3.3 Integration of Global Design Elements

For the final stage of the prototype, a plethora of considerations was made. First of all, the entire design is a solution to target a social and ethical dilemma. Even though this has the potential to improve lives, certain considerations still need to be made. Because of this, it is critical to follow a code ethics.

By making the prototype a 3D printable platform, it is hoped that it will be more accessible to the target audience. 3D printing, as time progresses, is becoming more accessible as it lowers the cost that goes into the production of these parts. It even creates a DIY environment where someone with sufficient technical background can set this up for a small cost when compared to other humanoid robotic platforms that are commercially available.

3.4 Feasibility Assessment

As shown in both CAD models, the parts designed can easily be 3D printed. Each part takes roughly between 5 to 8 hours to print, and is designed for easy assembly. As mentioned in the previous section, the availability of 3D printing, an increasingly available technology, and HCTeR's other components, allows for the feasibility of this design. Furthermore, by looking at the price of each individual component, a better understanding of the expenses that went into this project was analyzed. For the complete analysis of the total cost, see Section 6.5.

Finally, at this point in the design effort, with the physical structural design and component selection completed, it was decided that the programming effort would be limited to producing walking as the primary focus. As an alternative, crawling, which is a valid physical therapy exercise in pediatrics [9], may be explored.

4. ENGINEERING DESIGN ANALYSIS

4.1 Overview

From an engineering standpoint, HCTeR is designed to allow for some key kinematic goals to be met, maintaining a high degree of strength, and reduce costs as much as possible. Several simulation analyses are performed to ensure that these goals are met.

From a kinematic perspective, it was necessary for HCTeR's joints to have nearly the same degrees of freedom that the corresponding real human joints have. This allows for a reasonable range of movement in the robot's primary limbs that might be needed for child rehabilitation. Actuator performance and selection would prove to limit function rather than being limited by geometric parameters within this context.

Strength of design was important as well. Besides holding its own weight, HCTeR is designed with a factor of safety in mind which will prevent damage from normal wear and some harsher interactions with children. HCTeR is not designed to withstand severe impacts, but will be resilient within the context of rehabilitating a child under adult supervision.

Another major design focus was the widespread implementation of 3D printing as the primary method of manufacture. This, along with prudent research into components, made reducing the cost simpler. These were the major factors and considerations in the overall engineering design effort.

4.2 Kinematic Analysis and Animation

Because the goal of HCTeR is to reproduce a movement, teach, and encourage pediatric physical therapy patients, it is of utmost importance that the design process includes the proper limb motion.

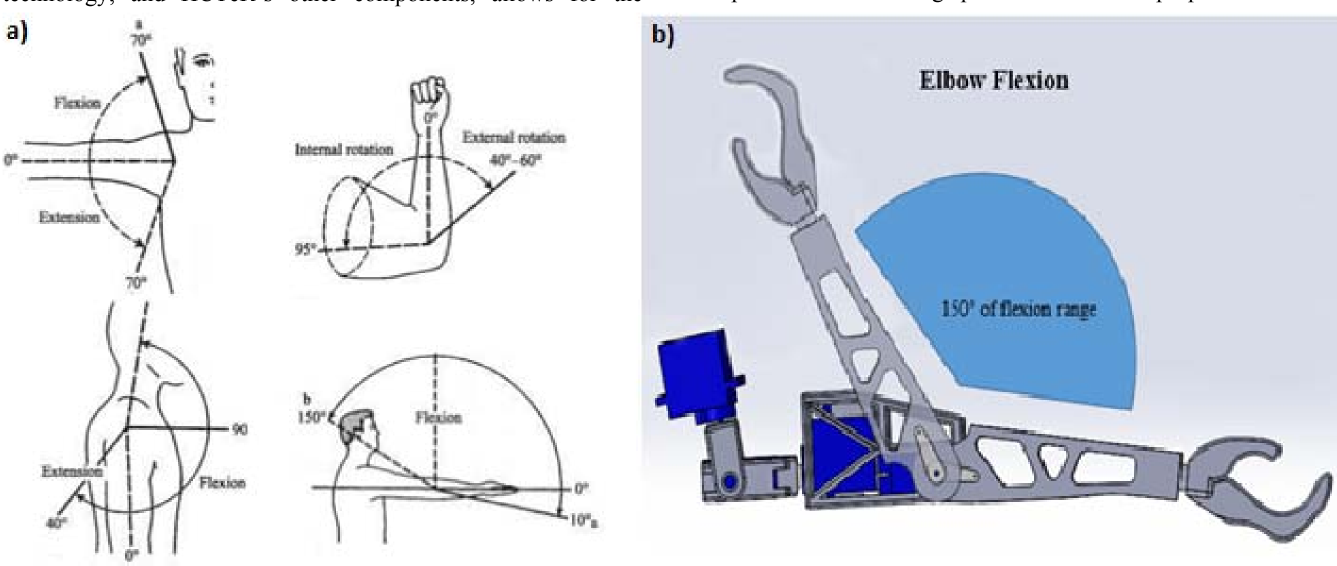

Figure 4. (a) Human Arm Kinematics. (b) HCTeR Prototype Elbow Flexion

By limiting the servo range of operation to that of an actual human child, HCTeR can be used to serve as a model for the child. Figure 4 (a) provides a geometric visualization of the range of the joints in a human arm compared to Figure 4 (b) which displays HCTeR's arm's range of motion for the first stage prototype design. As shown, the average human elbow has a range of motion of 150 degrees, stage 2 also provides this range of motion. However, stage 2 limited the internal and external arm rotation shown in Figure (a). This was a result of the choice to remove a degree of freedom in the elbow allowing more room for wiring in addition to reducing cost and simplifying the design wherever possible.

The programming, however, will be the ultimate control for the kinematics of the elbow and other joints. Likewise, the range of motions of each major joint of the human body (i.e ankle, knee, hips, elbow, shoulder, and neck) were analyzed to determine angular ranges of motion [10]. In general, the major movements were modeled with both the same degrees of freedom and angular ranges of a typical human body.

Because, the team decided to focus on reproducing human walking, ensuring that the set of joints comprising the legs were anatomically accurate with regard to both degrees of freedom and angular range was most important. From a chart by the Department of Social and Health Services, the following movements were recreated accurately:

Table 1. Summary of Joint Movements Available on HCTeR

Joint	Movement
Hip	Flexion, Adduction, Abduction, Backward Extension
Knee	Flexion
Shoulder	Abduction, Adduction, Flexion, Extension
Elbow	Flexion
Ankle	Inversion, Eversion, Flexion, Extension
Back	Extension, Flexion, Lateral Flexion
Neck	Rotation

4.3 Material Selection

In FDM, or fused deposit material, 3D printing, the most common materials are ABS and PLA. Both of these materials are known as thermoplastics, meaning that they can be easily molded when they are heated and can return to being a sturdy solid once they have cooled off. Based on research, it was determined that ABS is the stronger material. From the stress analysis, however, PLA was found to be strong enough to be able to withstand the more modest loads HCTeR will most likely encounter. In addition to this analysis, the group decided to use PLA for its added benefit of exhibiting lower warping when being printed [11]. Also, to make HCTeR more resilient, the group suggest that the printing be done with a 20% fill density.

4.4 Component Design

HCTeR's assembly process was documented and explained in an instruction manual allowing even someone with minimal experience with robotics to purchase and assemble all the components easily. Along with instructions for use and descriptions of the components, the instruction manual contains exploded views, wiring diagrams and schematic representations of all the components. For example, below is the exploded view of stage 2 design of HCTeR's right arm as for improved clarity.

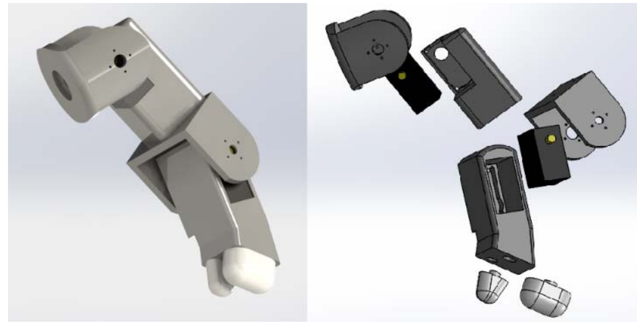

Figure 5. Exploded view of HCTeR stage 2 arm design

There is an important note to make regarding the engineering logic used in selecting the components described in Section 3. In the literature survey initially performed, one of the major issues identified with existing platforms is overall cost. The cost of many of these platforms is driven up significantly by the incorporation of proprietary microcontroller systems and very high capacity servos. As a solution to this, the Humanoid Rehabilitation Project prudently sacrificed performance and the benefits of proprietary controllers in order to reduce cost (i.e. less powerful servos and the ability to use software available for proprietary controllers which make control and programming simpler) in the hopes that the work carried on after the publishing of this paper will allow for these factors to be mitigated and adapted to the Arduino family of controllers.

4.5 Design Overview

Stage one of the prototype served as a learning curve for producing the version of HCTeR which is able to meet all the kinematic requirements. This prototype features a smaller scale that works best to model and gauge more accurately what stage two will be capable of. By creating the first prototype, a better analysis of the degrees of motion of each limb was achieved.

Stage two features a similar design, though structural improvements were made to ease manufacturability and improve function. A significant modification to this version is that the ability to perform forearm pronation and supination [10] were eliminated. This decision simplified the design, reduced cost, and did not significantly affect the ability of the robot to be programmed to perform the primary therapeutic function of focus. Finally, in this iteration of HCTeR, the use of a Bluetooth and wi-fi connectivity shields were finally ruled out as development of appropriate software was deemed outside the scope of this primary objective. However, because of the use of the Arduino family of controllers, future inclusion of these capabilities and the accompanying programming efforts is possible and will likely increase the effectiveness of the tool.

5. PROTOTYPE CONSTRUCTION

For HCTeR's prototype construction, the build was subdivided into segments. These segments were apportioned into smaller, electromechanical systems (i.e. individual arms, individual legs provided by Florida International University's 2017 Spring EML 4840 Robot Design course, Team F, isolated head unit, etc.). This approach allowed for a simplification of the testing and programming phase by isolating systems which could be developed concurrently. The software programming proved the most difficult aspect of development as the desired functions are extensive and complex. Prototyping proved invaluable in providing the groundwork for understanding of how to best utilize the 3D printer, revealing several physical design weaknesses, and in producing the majority of the programming to be used in the final design.

5.1 Description of Prototype

HCTeR is a simplistic humanoid robot whose function is as a tool for improving physical therapy. Fundamentally, the most critical aspect of the robot's function is its ability to replicate a movement which has a sufficient degree of anatomic accuracy. The other fundamental design challenge is to make the unit sufficiently distinct from the human form, to reduce the risk of social intimidation, while still making the robot appealing and physically relatable to a pediatric patient. Therefore, the initial build of HCTeR focused on these factors. A single, simple exoskeleton was used to produce the human-like shape and proportions of the central structure of the robot. The hollowed-out exoskeleton allows for material cost to be minimized while maintaining sufficient structural strength. Simulations of several loading conditions were performed in SolidWorks as part of the prototyping process as well as some rudimentary physical testing. The design philosophy behind the central exoskeleton extends to the HCTeR's simple legs and arms as well. Functionally, the limbs house the servos and wiring while allowing for the full range of movement. In order to fulfill the requirement to be engaging and appealing, visual graphics are incorporated in two LCD screen "eyes" as a principal feature of stage 2 HCTeR. HCTeR stage 1 stands about 43cm tall and 15cm wide in the prototype state assembly, while stage 2 will be modifiable to be the size of the patient.

5.2 Prototype Design

Each part is designed to connect at the servo motor, facilitating the assembly of the limbs. The servo motor serves as the joint between these parts. Bearings were introduced into the opposite side of the servos to create a near frictionless movement and support at the joints. In order to further facilitate the assembly, these joints were designed to be supported by eight screws. By carefully testing the model, the group was content with the chosen design of prototype HCTeR.

5.3 Parts List

5.3.1 Legs

Leg units incorporated into HCTeR are discussed in further detail in another work [12].

Each leg feature four servos providing a total of four degrees of freedom for each leg and are connected to a fifth servo at the hip which will allow for a total of ten degrees of freedom once the unit is assembled. The functionality of the legs should be precise enough to be able to walk while keeping the core, or center of mass, upright. Since the body is completely symmetrical, the center of mass is located closer to the hip which will help maintain the equilibrium required for walking and standing. The hip designed features an additional servo that will create the rotational movement of the torso parallel to the floor [12].

Figure 6. Leg design

This prototype leg unit also features a hidden chamber underneath the casing of the legs that will conceal the servos under the "toes", as well as the wires passing through the leg structure all the way to the core of the platform.

5.3.2 Head

Though the head doesn't perform any critical movements, it still has a major role in the development of the final design for this platform. The head is the most important aesthetic aspect of the robot when built to appeal to children since this is where the focus of the child will likely be when approaching this platform for the first time. An important consideration when examining a child's motor abilities is considering the increased unbalance caused by the larger proportional size of their heads to the rest of the body when compared with an adults. The platform will attempt to simulate this issue in order to create the same difficulties when standing up or performing other gross motor functions. For the prototype being built in stage 2, further improvements for this component must continue to be considered to include an LCD display, speakers, and other light sources.

5.3.3 Torso

The torso was built to be completely symmetrical while allowing for the placement of the head and arms. The torso shares the center of mass with the hip, so that the platform will be able to maintain balance while moving. To do this, shifting the center of mass around depending on the movement is essential in order to remain upright. Crucially, the center of mass will be determined by the placement of the battery and microcontroller as the most significant sources of mass within the torso. These two are attached inside the torso to create a larger center of mass in the mid region of the robot. A significant change which occurs in the torso between prototype and the second iteration is the enclosure of the structure by a shell. This will protect sensitive electronics and also reduce the risk to children of electrocution or stuck fingers.

5.3.4 Arms

A major change here between the first iteration and second is the removal of a servo and the internal and external rotation [10] functionality to reduce cost and simplify the design. After analyzing the size of the design compared to the servo, the group made the decision that this rotational movement is not essential. Further designs may improve this motion by adding smaller more costly servos. Two further considerable changes are the simplification of the hand in order to produce a less intimidating form and the enclosure of the skeletal frame in order to improve safety.

5.4 Construction

As mentioned before, a significant driver behind this design of HCTeR was simplifying the assembly as much as possible. This was done by creating the parts to fit the joints, servos, as smoothly as possible. The servos are then connected to the microcontroller and to the battery, the latter is only if required. Each limb has screw holes that create a support by attaching each part to a joint. The micro controller is then attached inside of the torso to allow the prototype to freely move around. If a battery is required, this battery is also attached inside of the torso.

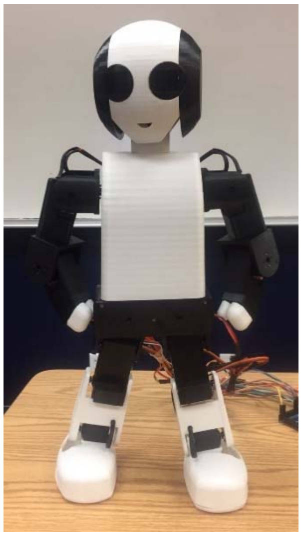

Figure 7. Final Design of HCTeR

6. DESIGN CONSIDERATIONS

6.1 Health and Safety

Ensuring that the solution created does not produce any unintended or harmful secondary effects is critical, especially for a platform intended for use with disabled children. IEC/NP 80601-2-78 is a document aimed at providing safety standards specific to "medical robots for rehabilitation." This standard is under development by the International Organization for Standardization (ISO) as of 2015 but is not yet published or available as of the publication of this report. Therefore, in order to guarantee the high degree of safety required, ISO 13482:2014, an international standard defining safety requirements for personal care robots, will be followed with prudence instead. It is important to note that this standard explicitly states that it does not apply to several classes of robots which include "robots as medical devices." However, the standard goes on to say that "the safety principles established in this International Standard can be useful for [robots as medical devices]" and is, therefore, a relevant reference publication to the project [14].

6.2 Assembly and Disassembly

Assembly of HCTeR is intended to be a straight-forward, accessible process. Structurally, HCTeR will require off-the-shelf components which will be fastened to a 3D printed structure via hardware specified in components. Electrically, all the components are housed in the enclosed torso.

6.3 Manufacturability

From a manufacturing standpoint, the bulk of the process relies on the increasingly available technology of 3D FDM printing. Costs of purchasing units capable of creating all of HCTeR's structure have plummeted within the past few years, with printers available for as little as $300 [15]. Furthermore, shops with these capabilities which charge hourly rates for printing are becoming increasingly common and produce high quality projects. Electromechanical off-the-shelf components will be specified which are widely available and which are cost effective.

6.4 Maintenance of the System

HCTeR will require no special maintenance. Because the structure is almost entirely plastic and all mechanical actuators are small and electric, lubrication will not be required. Basic sanitation may be required as the device may be in contact with multiple children.
In addition, in the case of a significant break or failure, the robot is modular and replacement parts can be easily obtained and integrated into the unit. If the user has access to a 3D printer, the broken part can be downloaded and reprinted printed. If the broken part is at the component level, these components can also be purchased from many major retailers.

6.5 Economic Impact

After having completed the construction of the finalized version of HCTeR, a cost estimate is provided for replication of the device. In Table 2, we find the components, cost of filament, etc. that have been chosen for the final prototype of HCTeR. Immediately, the group realizes that a modest reduction in the total price can be achieved by changing the servos in the joints that do not require a large amount of torque, such as the neck, to a smaller, more economical servo, such as the SG90. Other components, such as the Arduino Mega, can be changed to comparable open source components. In the case of the above mentioned, the Arduino Mega is valued at $45, while the Funduino Mega is valued at $14.75. In the case of these microcontrollers, the schematics and functionality are the same. As a main objective of the project, reducing the economic impact of producing and utilizing this tool is paramount to ensuring the degree of accessibility desired.

Table 2. Component Cost Estimate

Component	Number of Parts	Price
Funduino Mega	1	$14.75
LCD	2	$10.88
Sound Module	1	$8.36
Servo	18	$107.82
Filament	2	$44.00
Wiring	50ft	$12.00
Wire Protector	1	$7.97
Ball Bearings	40	$16.65
Gyroscope	1	$3.00
Battery	1	$39.99
	$\sum$	$265.42

Furthermore, Table 3 breaks down the total manufacture cost, if one is required, of the design. Considering this design as open source, the availability allows for the need of a manufacturer to be unnecessary to anyone with access to a 3D printer ignoring labor costs. It is important to note that this analysis was performed with a manufacturing cost of $6 per hour. Costs estimates based on this is provided in Table 3.

It is important to note that the printing not only depends on the size, its shape is also of utmost importance. For some parts, a "raft" support is needed underneath the part that will increase the overall printing time. The fill density also plays a major role in the total printing time. If the components of HCTeR had been printed in a bigger 3D printer, such as the ones used by manufacturers, the total amount of printing time could total half of our current printing time.

Table 3. Manufacturing Hours and Cost

Component	Number of Parts	Printing Time (hrs)	Cost
Head	1	13.2	$79.20
Head - Left Side	2	6	$72.00
Neck	1	5.2	$31.20
Chest	1	21.6	$129.60
Chest - Back Part	1	15.1	$90.60
Shoulder - Servo Support	2	1.3	$15.60
Shoulder	2	3.5	$42.00
Arm - Upper Section	2	2.6	$31.20
Elbow	2	2.5	$30.00
Forearm	2	4.2	$50.40
Finger	2	0.7	$8.40
Thumb	2	0.3	$3.60
Hip	1	6.8	$40.80
Hip - Front section	1	3.1	$18.60
Hip - Servo Support	2	2.2	$26.40
Hip - Servo Support Front Section	2	1.2	$14.40
Leg	2	3.7	$44.40
Calf	2	1.9	$22.80
Calf - Side Section	2	1.7	$20.40
Ankle	2	1.8	$21.60
Sole	2	4	$48.00
Foot	2	6.8	$81.60
Foot - Servo Support	2	0.8	$9.60
Bearing Holder	12	0.3	$21.60
		Totals ∑	$954.00

7. DESIGN EXPERIENCE

Overall, the design experience was impacted tremendously by a number of factors. The most defining and difficult of these factors was framing the original problem. The initial idea of using a humanoid robot to improve the quality of physical therapy for children with cognitive disabilities was presented to us by PhD candidate Melissa Morris. However, the prompt was still a fairly open concept. Isolating a significant issue within this medical context which could be addressed with a mechanical solution became the primary effort.

Because of the complexity of the kinematics of the human body, creating a robust humanoid model is incredibly challenging. This first consideration presented a limitation which was accounted for by sacrificing robustness of the model for ease of design, construction, and implementation. Sacrificing robust functionality also directly led to lowered costs of production. Therefore, it was natural for the design effort to focus on the less complex gross motor skills which concern physical therapists rather than fine motor skills which are trained by occupational therapists. This allowed for the solution to focus on issues within the context of physical therapy alone.

Defining the social problem to be addressed became the second area of interest. Research conducted into the field of pediatric rehabilitation yielded a common and pronounced problem of a related nature. According to Autism Speaks, "individuals with autism have a great deal of difficulty with social interactions" which is compounded by the fact that "children with autism frequently have challenges with motor skills such as sitting, walking, running or jumping." The need for physical therapy is increased with these conditions while the delivery of treatment is also made more difficult by the fact that these children are less likely to behave favorably around therapists. The issue then can then be summarized as a learning barrier which exists between the two. This set of challenges characterizes the need for a solution. Therefore, the design solution needed to be a teaching tool which could help bridge the social gap between physical therapists and patients. By utilizing a humanoid robot whose physical design allowed it to perform the required movements and exercises, but which also had design elements intended to capture a child's attention, the robot could serve as a teaching model that causes less stress or discomfort than interacting with another human might induce.

Finally, because of time constraints and the interest in creating a modular platform solution, the robot needed to be designed with "room" to be capable of performing other functions which may not be explored or defined in this iteration of implementation. In essence, the project selected some simple functions, such as sitting or walking, to explore as a "default" configuration and created a robotic structure which could be programed to perform differently or modified to include different components.

7.1 Contemporary Issues

During the duration of the design experience, it was desired to create a solution to a problem within the context of society and our world today. Centers for Disease Control and Prevention (CDC) has released a study confirming "1 in 68 children (1 in 42 boys and 1 in 189 girls) as having autism spectrum disorder (ASD)" [16]. In the 1970's, the CDC reported rates closer to "1 in 2,000 children" as having been diagnosed with autism. There is much debate in the media today about whether these rates are increasing dramatically or if the increases are caused by the fact that the definition of autism has been broadened recently. Regardless of the causes for the increase in cases, the simple fact that more of these patients are being treated has exacerbated the problem faced by many areas of the medical community: interacting and treating patients who are socially unresponsive or behave atypically.

7.2 Life-Long Learning Experience

As a team, the project led to a thorough and complete design process which mimics the design environment of industry. For all the members of this team, this was the first complete design process carried out with such robustness and to completion of a unique solution.

As individuals, each member gained invaluable insight into the complexity of completing a full design. The members learned the importance of defining the problem well and the steps taken to create a solution to the identified problem while maintaining focus and keeping the design feasible and within the scope of necessity.

8. CONCLUSION

The Humanoid Rehabilitation Project sought to create a modular, robotic platform which could be used as a teaching tool that also mediated between physical therapists and patients. In particular, the design efforts were focused on bridging a treatment gap which often exists between children who have certain cognitive disabilities, and the therapists who are treating them. Children with these conditions can be generally less-responsive to adult strangers such as physical therapists or can become stressed by interacting with others.

In an effort to alleviate this issue, HCTeR is an appealing, accessible, and unintimidating robot who can be programmed to demonstrate a gross motor skill, such as walking, while downplaying the human interaction element of therapy which impedes progress otherwise.

HCTeR is physically designed to be functional and inexpensive. Through the rigorous design process, a default configuration of components and structural design was established for HCTeR which will allow him to perform his core functions at a minimum cost. However, because of the open source and modular nature of the project, individual applications and constructions of HCTeR are still possible to vary functionality.

Within the physical configuration of HCTeR, functions can be created to serve a widely variety of needs. Through the use of coding, a program may be produced to allow HCTeR to perform any range of movement allowed by the physical configuration. However, the most significant existing limitation of this platform remains the programming process and, thus, a higher level software solution which takes advantage of an interactive user interface or other input device such as motion capture needs to be explored in order to maximize the potential of HCTeR. Because the default physical configuration is based on a real child, a good approximation of the kinematics of nearly any gross motor skill can be recreated through the application of the code.

8.1 Future Work

HCTeR, as a central design tenant, was created to be improved over time by the future teams and end users themselves. This modular nature is seen in many facets of HCTeR. For example, the default configuration, which incorporates the most basic components needed to perform a function such as walking without aid, can be modified or replaced as needed to improve functionality.

The addition of a gyroscope sensor which will provide a sense of balance at the hip may allow for a function such as walking without assistance or running to be accomplished. Additionally, HCTeR's code can be edited to produce different similar humanoid joints movement. The current configuration of components and coding also concern a limited number of gross motor skills. With further development, a broader selection of motor-skills and therapy options will be possible. A source for a downloadable library and most importantly, a higher level programming solution, is a crucial aspect in the furtherance of this project, as the foundation of this project is expanding accessibility for the users.

Another future functionality to be added concerns enabling control over long distance. wi-fi compatibility will allow therapists to issue commands or modify HCTeR's coding remotely. A telemedicine functionality could greatly reduce costs of use and increase availability as well.

9. ACKNOWLEDGMENTS

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