Theoretical Modeling and Parameterization of a Novel-Actuator-Based Transtibial Pediatric Prosthetic

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1. Abstract

Dependability is a key factor for the widespread adoption of powered prosthetics, achievable through longer battery life, lighter weight, and affordability. This presents the need for a high-efficiency scalable actuator that provides form-fit-function for pediatric-to-adult prosthetics. Currently, powered prosthetics are built around state-of-the-art electromagnetic motors and gear components that lack scalability and efficiency for mobility. The presented Smart Fluidic Servo Actuator (SFSA) utilized a built-in-design approach, involving every component as an integral part of the mechanism to address these limitations. Last year's proof-of-concept evaluations of the SFSA established the efficacy of a valveless fluidic transmission through the adoption of a novel motor control principle. To establish the capabilities of the SFSA in a transtibial prosthetic, theoretical modeling and parameterization were done during this year. Compensating for the unavailability of pediatric mobility data, empirical studies were conducted that logged the ground-reaction-force of a pediatric subject with a specially-designed force-plate and generated joint parameters. The CAD model of the prototype ankle incorporates low-friction graphene-coated pistons and a high-flow programmable displacement pump. All components were designed for additive manufacturing. Theoretical modeling, SolidWorks finite element analysis (FEA), and simulated motion analysis studies showed that the SFSA can generate 50 Nm torque at 5.4 radians/second speed with 120-watt power consumption (40% of the state-of-the-art prosthetic ankle joint). Further work includes design optimization followed by prototype assembly and evaluation. The overarching reach of this work will improve the quality of life for users of all ages.

2. Introduction and Background

The advancement of technology has brought changes to the options for prosthetics in today's world. In recent years, with the development of high-density magnets and advanced manufacturing processes, electric motors have achieved more than 90% efficiency. aiding in the development of smart machines. Today's actuators are predominantly electromagnetic (EM) motors coupled with high-efficiency gear reducers to convert motor speed to the required torque. EM motors tend to draw higher electric power to produce more torque. Thus, there is a balance of output mechanical torque and input electric power. This becomes very critical when actuators are used for mobile devices/applications, where the electric power source is limited. Significant developments in mobile processors, display components, batteries, and related technologies have enabled today's smartphones to meet the ideal power-to-weight-to-size ratio to achieve the power of a computer with a single charge per day. Similar efforts are needed in actuator technologies, which will enable mobile devices such as powered prosthetics, exoskeletons, bionic limbs, and smart assistive devices to be more dependable and adaptable. Aerial drones have pushed the boundaries of high-speed, low-torque, optimized power EM motors and eliminated the need for any additional mechanical components like gears, which makes them direct drive (DD).

However, DD-EM motors still lack scalability for low-speed, high-torque applications. For an application that demands high torque actuators, the usual combination is of EM motors with suitably configured gear reducers to convert the high speed to required torque and speed. However, these combinations reduce the overall efficiency and do not reduce the input power. Compared to today's mobile computing devices, mobile devices which have EM actuators used for continuous rotation/propulsions still do not have the luxury of long-lasting battery power. Drones or electric vehicles have the option of battery swapping or fast charging but this limits the uninterrupted usage profile. Overall, battery usage of actuator-based mobile devices is still considerably low despite the development of high-strength magnets and related manufacturing technologies. Powered prosthetics are most often actuated using the same or similar methods, which involve motors paired with geared transmissions or linkage bars (Azocar et al., 2020, Lawson et al.; 2014, Simon et al., 2014; Alcocer et al., 2012; Sinha et al., 2011; Windrich et al., 2016), thus suffer the same battery life. The power efficiency of motor-driven mobile devices has reached a critical point, as most components have already been heavily optimized.

This flaw in EM actuators heavily affects smart prosthetics adaptability as compared to a powered wheelchair or other assistive devices. Bionic limbs are already inaccessible to most due to price; only 10% of children with major lower limb loss have regular annual medical visits for prosthetics, and powered prosthetics can cost up to $70,000 with insurance (McLarney et al.; McGimpsey and Bradford). The other options for prosthetics, passive and semi-active, are less costly but provide limited function(s) (Windrich et al.). A different approach is required to address the need for a scalable and configurable actuator that will have a power-to-weight-to-size ratio comparable to today's smartphone. One option is improving motion transfer efficiency specific to discrete/controlled motion applications. This research is based on the novel concept of combining the high efficiency and controllability of EM motors with suitable hydrostatic transmission through advanced control methods to achieve fluid like motion through programmable fluid flow. However, unlike traditional electro-hydraulic actuators (EHAs) which use valves, sensors and complex fluid lines the proposed actuator relies on novel control method and valveless innovative fluid line with the intent of developing a dependable joint mechanism that is scalable, customizable, configurable, affordable, and dependable. Incidentally, powered prosthetics for pediatrics particularly are a severely under-developed sector due to lack of form-fit and dependability; most pediatric prosthetics are retrofitted using components used for adults. Although cost is a big factor, scalable powered prosthetics for pediatrics that can sustain a typical usage time frame in a single charge is far from reality. Commercially available powered prosthetics do not specify battery life, indicating it is still not standardized. Additive manufacturing technologies have helped tremendously by making body-powered hand prosthetics accessible to all regardless of financial status (Ferreira et al., 2017). On the other hand, electrically powered prosthetics are becoming very popular and several companies are offering commercial solutions. However, solutions for pediatrics are very limited; only one company was found to be offering exclusively pediatric components.

Inspired by recent developments in soft actuators for soft robotics, fluidics, and additive manufacturing technologies, this proposal presents the concept of a dependable and adoptable ankle prosthetics using the smart fluidic actuator.

The proposed concept convertes fluid flow generated by an EM motor-driven positive displacement pump through an integrated fluidic actuator for mechanical power generation. Here, the EM is not directly responsible for torque generation; instead, there is a conversion of fluid flow to force/torque. This will enable the use of a comparatively low torque motor that demands less electric power in typical usage. The proof-of-concept validation from last year established the feasibility of the smart fluidic actuator for knee and/or ankle joints that has the potential to provide the required joint torque-speed profile with better electrical power efficiency. Earlier work tested several combinations of positive displacement pumps and fluidic actuators, an effective attempt to deal with the issues of state-of-art EHAs while retaining their beneficial attributes. This work revealed that the optimal design involves pairing a positive displacement pump with a linear actuator (piston-cylinder pair) to produce adequate force at the lowest power consumption. This year's work created a model of the actuator and enabled it for parametrization for scalability leading to designing a ankle prosthetics.

3. Methods and Materials

3.1 Experimental Design

The overall concept of the actuator for the ankle prosthetics is shown in Figure-1. A pair of antagonistic double-acting cylinder-pistons is connected to a programmable positive displacement fluid pump and given a term as a programmable flow generator as shown. Ports on one end of each cylinder are connected to each port of the pump to provide active pressure flow. Ports on other ends of cylinders are directly connected to support reaction pressure flow. The reaction pressure flow acts as an hydrostatic energy storage chamber. The piston rods are connected through a polychain belt over an output drive pulley. For large motion range, unlike other EHA-based prosthetics, a belt-pulley mechanism is selected. The 55mm-stroke of the piston can generate >60° of rotation. This range can be altered by increasing or decreasing the piston stroke, fulfilling the scalability, customizable and configurability. The footplate is directly attached to the output pulley. The programmable flow generator has two options that can adopt multichannel peristaltic version or external gear type version. While the peristaltic version has a max pressure limit to 125 psi, external gear type can go higher than 400 psi.

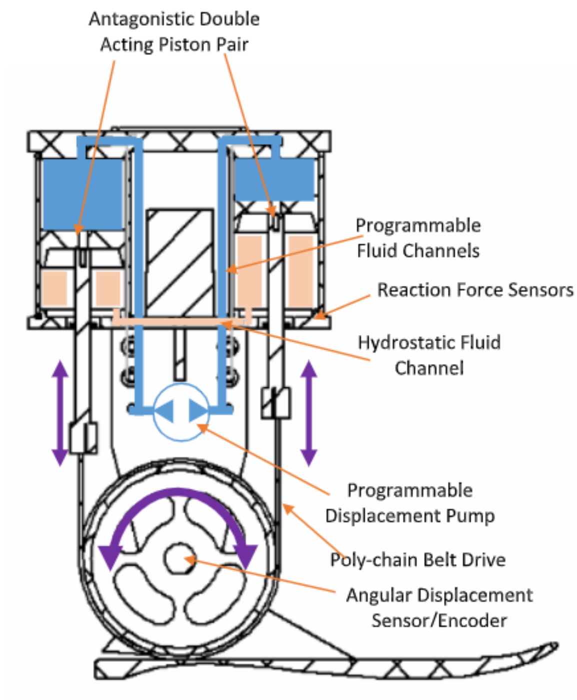

Figure-1: Conceptual Representation of the SFSA as Ankle Prosthetics

The entire project execution has been shown in the block diagram shown in Figure-2.

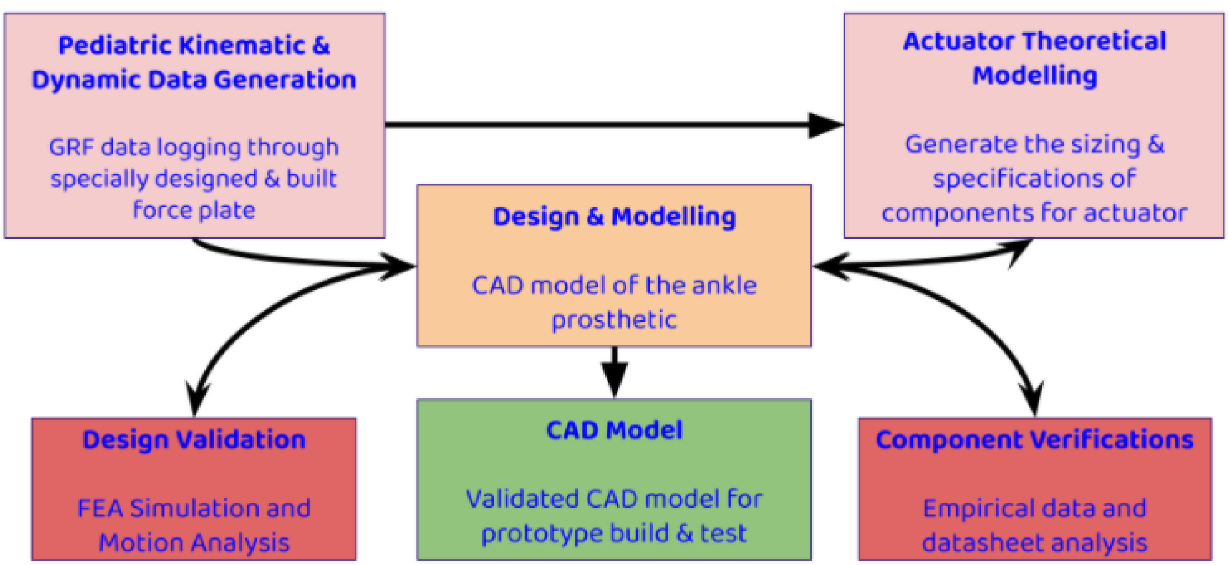

Figure-2: Project execution flow chart

Due to the lack of pediatric mobility and physical data, the project first necessitated the collection of subject data on physical measurements and ground-reaction-force (GRF) to derive mobility data. For simplicity, a female 8-year-old subject was chosen for data collections. Both legs foot length, ankle-to-heel length, ankle circumference, shin length (defined as the distance between the middle of the kneecap to the ankle bend), the calf circumference at two different points, knee circumference, and the widths of the toes and heels. Dynamic data was logged from sequences that included the subject first walking onto and off of the platform for standing data, squatting on the platform for squatting data, and walking over the platform for walking data. Each activity was done ten times, from which average GRF values were extracted per activity.

Subject data acted as a base-line standard for parametrization of the model. From there, static motion analysis and FEA were performed. The model underwent several iterations where material type, component shape and structure, and other aspects were altered based on findings from the simulations. Simultaneously, the model was verified using datasheet analysis and calculations. This all culminated in one final optimized CAD model of the prosthetic.

3.2 Materials

There were two parts to this project: the subject testing and the CAD modeling/simulations. The force plate used for subject testing consists of two identical pieces of plywood with dimensions 24x24x¾ inches, a Raspberry Pi 4, four 200kg button load cells, and a Phidget 4-Input Wheatstone bridge. The calibration process and program were supplied by the mentor. All modeling and simulations were done on SolidWorks 2021.

3.3 Criteria

The criteria for the prototype are based on adult human generic dynamics data as well as kinematics and dynamics data collected from subject testing. From human generic dynamics, the prototype is expected to have dorsiflexion of 20° and plantarflexion of 40°. The goal speed is 60 degrees per second, which is a 20% increase from a human ankle's speed. This increase in speed was made to act as a safety factor. Subject testing yielded dynamic data for standing, squatting, and walking torque, as well as kinematic physical measurements (shown in tables 1 and 2, respectively).

Table 1: Average Dynamic Empirical Data

	Average Torque (Nm)	*Average Speed (m/s)*
Standing	33.009009	N/A
Squatting	31.5002985	N/A
Walking	23.1086295	0.6553547824

Table 2: Kinematic Data

Distance	Left Leg (in cm)	Right Leg (in cm)
Foot Length	23.5cm	24cm
Ankle-to-Heel Length	6.75cm	6.75cm
Ankle Circumference	22 cm	22 cm
Shin Length	32.5cm	32.5cm
Calf Circumference (largest)	28.9cm	32.25cm
Calf Circumference (mid-height)	28.9cm	30.25cm
Knee circumference	40 cm	40
Heel Width	5.84cm	5.84cm
Toe Width	8.89cm	8.89cm

The main limitations of this project rise from the lack of pre-existing kinematic and dynamic data available for pediatrics. Extensive research did not yield accessible data, necessitating empirical data collection from human subjects. With COVID-19 restrictions only a single subject was considered.

4. Results

Data from empirical study, proof-of-concept tests (last year's work) and literature research were effectively utilized to formulate the theoretical model (Table 3) of the smart fluidic servo actuator (SFSA). Developing the force plate and data logs (Tables 2 and 3) from human subject tests augmented the lack of pediatric mobility and physical data. Efficient component combinations, specifications and performance envelopes through literature research and mentors' prior-art knowledge were identified. Ankle-specific actuator parametrization was done keeping normal joint range, torque, and speed as the target specifications size, weight, and the scalability factor for pediatric to adult form-fit as the design variables used for first version of CAD modeling. The 98-99% efficiency of the piston and belt drive, as well as the 90% efficiency of the fluidic pumps have been considered (Casey). Static force/pressure/torque FEA simulations on SolidWorks identified fatigues on corresponding components (examples: Figure-3)

Table 3 - Calculated Prosthetic Performance Based On Different Parameters

Actuator Kinematics						Actuator Dynamics			
Cylinder Dia (mm)	Piston Stroke (mm) *	Torque Arm (mm)	Piston Area (m^2)	Cylinder Volume (m^3)	Joint Range (deg)	Pump Pressure (psi)	Pump Pressure (N/m^2)	Estimated Force (Kg) **	Estimated Torque (Nm) **
50.000	55.000	50.000	0.0020	0.00011	60.0	125.000	861845.00	172.500	84.611
44.450	55.000	50.000	0.0016	0.00009	60.0	125.000	861845.00	136.331	66.870
25.000	55.000	50.000	0.0005	0.00003	60.0	400.000	2757904.0	138.000	67.689

* Derived from SolidWorks motion analysis

** co-efficient of friction for piston and volumetric efficiency of flow generator is ignored due to use of graphite piston/graphene coatied piston and non-continuous fluid flow, no temperature change and moderate operating pressure respectively.

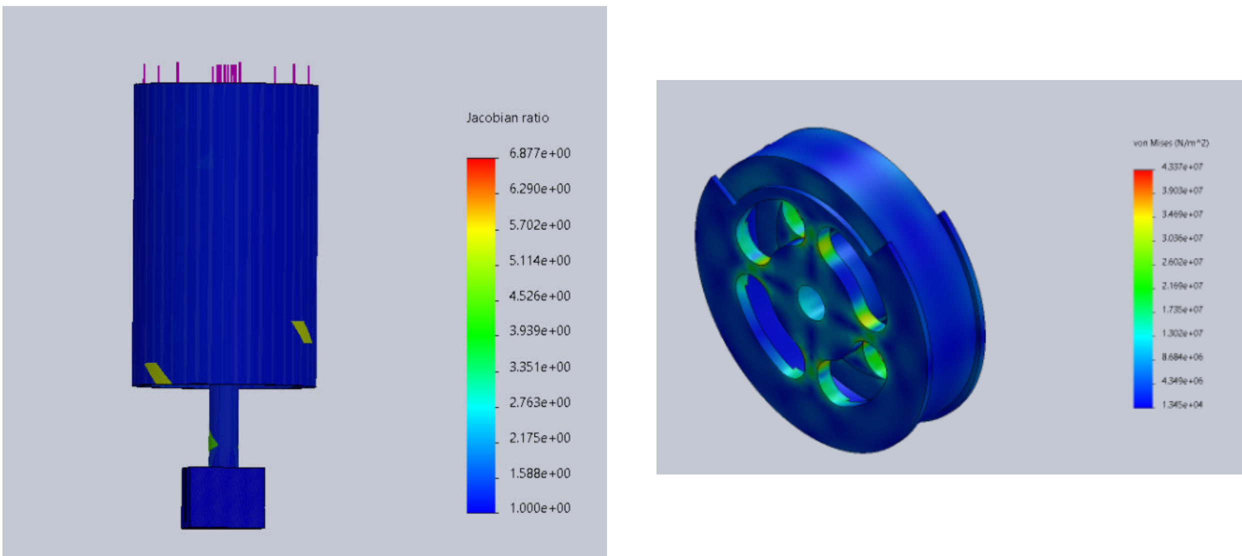

Figure - 3: Static FEA of Cylinder-Piston-Piston Rod (Left) and Output Pulley (Right)

Several iterations were made to achieve a CAD design matured for prototype build.

- Adding larger surface area to piston rod connection.
- Changing materials
- Increased thickness to the output pulley
- Adding structural ribs to the side plates

The current model shown in Figure-4 has 1.7 kg total mass, including battery and covers. The bulk of mass is from the foot and top connector pending optimization

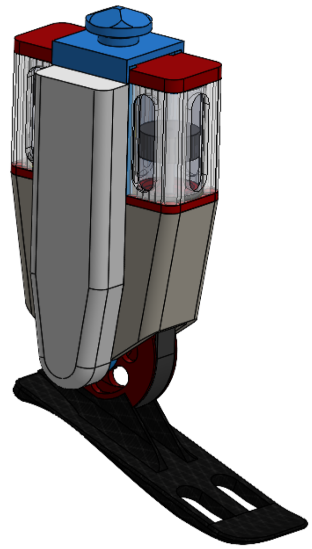

Figure-4: CAD Rendering of the SFSA Based Ankle Prosthetics

The flexibility of providing larger joint ranges (for knee joints) with the same design architecture— timing belt transmission—was choosen and the ratio was validated through motion analysis (>98% efficiency ("Timing Belt Advantages & Disadvantages | Pfeifer Industries"). A belt drive has the additional advantage of providing compliance, which is being designed to provide dynamic force sensing upon ground contact. Previous rocker arm versions tested during the proof-of-concept phase had issues with loss from friction as well as rigidity. Total scope of work has established that.

- Functionality of actuator: can easily scale up and down to accommodate user needs.
- Scaling, configuring for form-fit yet to be proven. Need to validate, modify using larger physical measurements data
- Affordability is inherent with the core design, supports the use of off-the-shelf components, 3D printable parts and simplified generic components

Table 4 shows estimated cost to be $1800, much less than other costs

Table 4: Estimated Weight and Cost of the Smart Ankle Prosthetic

Part/Component	Description	Weight (Kg)	Cost (US$)
Flow Generator	Coreless/Iron core motor	0.1	250
Low Friction Piston	Graphatie+steel reinforced piston	0.01	20
Cylinder	Engineered Glass Cylinder	0.026	20
Piston Rod and Bush	SS Rod with rod guide	0.07	30
Timming Belt	Poly-chain or similar belt	0.15	30
Output Pully and bearings	Timming puley with bearings	0.18	50
Side Plates	Structural side plates with channel	0.312	100
Primary Plate	Top holding plate with internal channel	0.09	50
Secondary Plate	Reaction pressure plate with internal channel	0.075	50
Motor Controller	BLDC/DC Motor driver and controller		300
Actuator controller	Main processor		300
EE Accessories	Encoder, sensor and accessories		250
Covers and Mechanical Items	Covers, brackets, bearings, O-rings, fasteners and accessories	0.727	350
	Estimated Total	1.74	**1,800.00**

5. Discussion and Conclusions

The theoretical model of the smart fluidic servo actuator was successfully formulated. Through research and mentor's prior-art knowledge, components with the best efficiency were selected, which lead to the parametrization of an ankle prosthetics. Component datasheets and parametric data from theoretical models (Table 3) were used to design and model the ankle prosthetics in SolidWorks CAD. Figure (2) shows a cross-section of the prosthetic to illustrate the actuator. A pair of low friction piston in an antagonistic arrangement coupled with a timing belt-pulley drive has been chosen. Different from last year's work, a belt-pulley transmission was selected for flexibility and a larger joint range. Additionally, a new aspect was introduced: dynamic force sensing during ground contact by utilizing the antagonistic response of the rigid-flex characteristics of the belt. For comparative performance analysis, a multichannel peristaltic pump and external gear pump driven by a DC brushed/brushless motor has been incorporated into the design. Simplified fluid channels with minimal resistance have been designed into the structural parts of the actuator. The flow generator's internal features were integrated into the structural components. The preliminary CAD model was used for static analysis for structural rigidity and load bearing validation through SolidWorks' finite element analysis (FEA) simulation. Several iterations were made to the CAD model to meet the required specifications of the prosthetics functional parameters. Modifications included an increase in the surface area between the piston rod connector and graphite piston, a material change to the output pulley, and load bearing ribs to the structural side plates. SolidWorks' motion analysis was performed to validate the scalability of the design's functional parameters to support pediatric to adult specifications. Form-fit validation is yet to be validated through larger physical measurement data. Affordability is not a concern as the design incorporates off-the-shelves components, and 3D printed as well as simplified custom parts pushing cost burden on the control software. The total cost was estimated to be around $1800 (Table 4), which is significantly less than the $5000-$70000 price range of typical powered prosthetics (McGimpsey and Bradford).

As the majority of the project was theoretical estimation and simulations, sources of error were minimum. However, errors did occur in the subject testing. Firstly, the subject's fatigue over the course of the GRF testing was not taken into consideration when accounting for measured data. Secondly, the force plate's accuracy was confined to a central area of the platform since all four load cells were calibrated together, where an error of ±3 kg existed in measurements.

The dependability aspect is pending validation, as it can only be proved through prototype testing to support the theoretical estimation of the power usage. However, the estimated current draw from the motor at highest torque and speed has a 2x safety factor to compensate for the lack of prototype data. A mathematical simulation incorporating the control scheme and corresponding design iteration will be done as part of future work to build the functional prototype. Prototype test and validation will be done through a specially designed test fixture to justify the dependability and functionality. Other goals are to eventually incorporate energy harvesting and myoelectric sensing into the prosthetic. Myoelectric sensing will make for a more intuitive human-limb interface, while energy harvesting technology can utilize ambient energy to power the prosthetic, allowing the power needs of the battery to be decreased.

The proposed actuator design has been theoretically proven to be an adoptable joint for a typical day full of pediatric prosthetic usage, addressing key concern of dependability for a longer usage time in a single charge small battery pack.

6. Acknowledgements

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