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

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Literature Review

- Prosthetics either passive, semi-active or active (Windrich et al.)
  - Passive, semi-active most simplest: either have no joint, or joint flexes through proximal muscle or spring-based flexion
    - Cheaper/more accessible but not enough functionality (Windrich et al., Azocar et al.)
  - Active have powered joints controlled through electromagnetic signals
    - $5000 to >$70,000 WITH insurance, large battery pack for longer usage makes it bulky, heavy and expensive (McGimpsey and Bradford, Azocar et al.)
- Only 10% of children with major lower limb loss have regular annual medical visits for prosthetics (McLarney et al.)
  - Prosthetics are **not consumer products:** every prosthetic is highly individualized
    - Lack of scalability in pediatric prosthetics "complicated by the need to address the child's growth and development" (Cummings et al.)
- **Price of prosthetic construction, fitting, and subsequent medical visits and purchases can quickly add up**
- **Root of the problem:** how the actuators function
  - Battery-powered mobile actuators suffer efficiency loss from the motor, transmission, lack of options for battery Actuator architecture does not provide scalability to support age-related growth
  - Components derived from industrial automation machines inflates costs
- **Solution:** actuation method with higher electrical & mechanical efficiency, with 3D-printable design
- **Concept:** Electric to mechanical energy conversion through state-of-the-art electric motor to generate hydrostatic force and generate required motion
- *Why hydraulics?*
  - Electric motor/gear/linkage systems heavily optimized, stagnant development
  - Proposed that fluid controlled mechanisms will be better for actively running children over three years (Cummings et al.)
    - Previous attempts at fluidic actuators in prosthetic use some sort of elastic element (Huang et al.)
    - Hydraulic prosthetic had exterior hydraulic power supply, which is unwieldy and unpopular (Windrich et al.)
- **Utilize best of both worlds**

Figure (a): electro-hydraulic ankle prosthetic (Huang et al.)

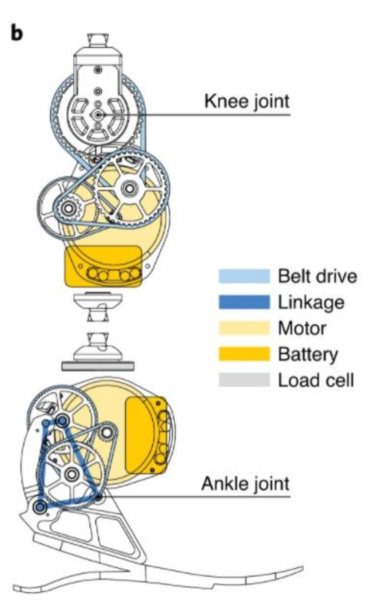


Figure (b): electro-mechanical actuator prosthetic knee and ankle (Azocar et al.)

Problem Statement

There is a need for a dependable joint mechanism that is scalable, customizable, configurable, and affordable.

Last Year's Work

- Work process: tested three different proof-of-concept designs for electro-hydraulic actuators, compared performance parameters, and derived best design combination (Fig.-C)
  - Designs tested: peristaltic & vane, internal gear & vane, peristaltic and dual-cylinders
  - Empirical study on proof-of-concept prototypes to find power density, compared to state-of-art
    - Best design: combination of a peristaltic pump with two cylinders
      - Had highest torque density (113.30 Nm/kg) among the three presented designs

Table 1: Performances from Empirical Study

	Design A	Design B	Design C	UMichigan*
Torque Density (Nm/kg)	2.67	2.67	113.30	27.03
Torque (Nm)	0.80	0.80	56.65	47.00
Weight (kg)	0.30	0.30	0.50	1.74

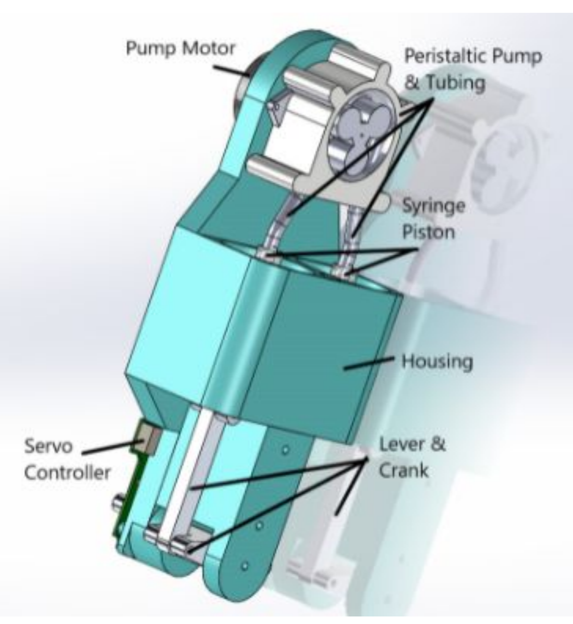
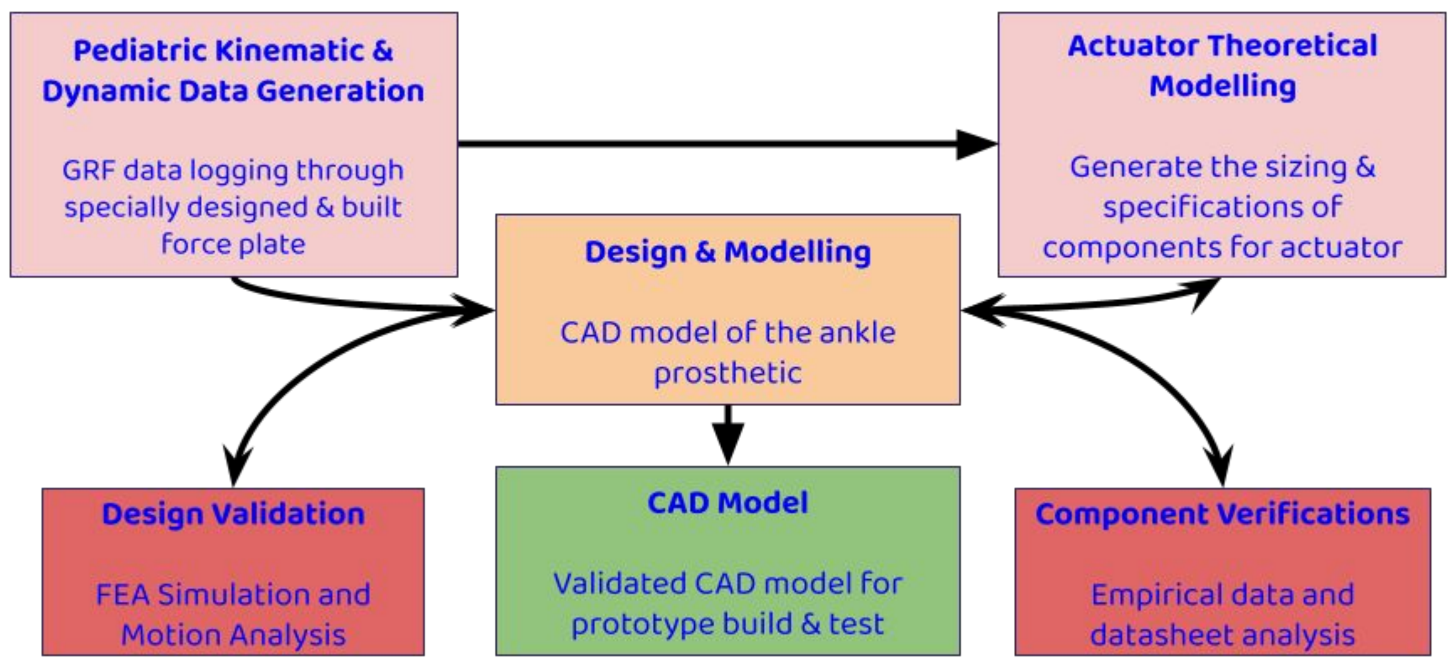


Figure (c) - Left: last year's best design; design c

Experimental Design

Mentor gave assistance in force plate set-up, simulation type selection and execution



Constraints and Criteria

- Criteria (target specifications for prosthetic)
  - Dorsiflexion and plantarflexion total of 60°
  - Speed of 60 degree/sec (20% increase from human speed as a safety factor)

Table 2: Physical Measurements:

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

- Constraints:
  - Lack of pediatric kinematic/dynamic mobility data
  - Accessibility to larger subject group for data collection
  - Time

Table 3: 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

Results

Table 4 - Calculated Prosthetic Performance Based On Different Parameters

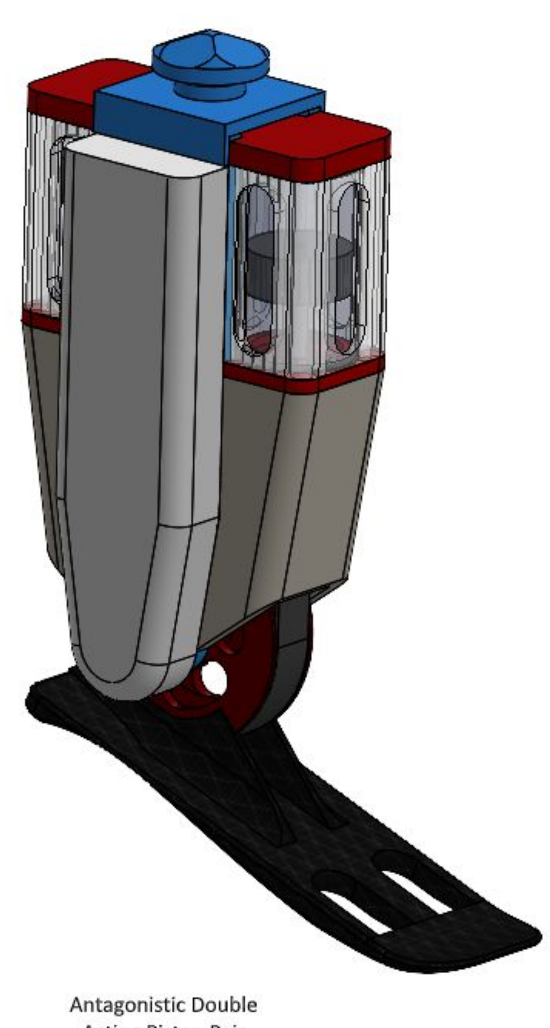
	Actuator Kinematics					Actuator Dynamics			
Cylinder Dia (mm)	Piston Stroke (mm) *	Torque Arm (mm)	Piston Area (m^2)	Cylinder Volume (m^3)	Joint Range (deg)	Pump Pressure (psi)	Pump Pressure (N/m^2)	Estimated Force (Kg) **	Estimated Torque (Nm) **
50.000	55.000	50.000	0.0020	0.00011	60.0	125.000	861845.00	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

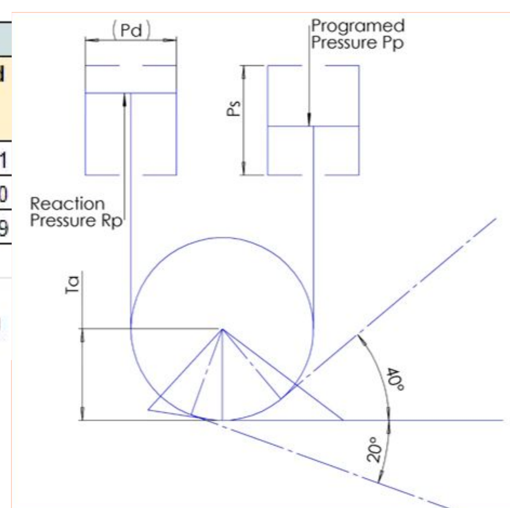
* Derived from SolidWorks motion analysis

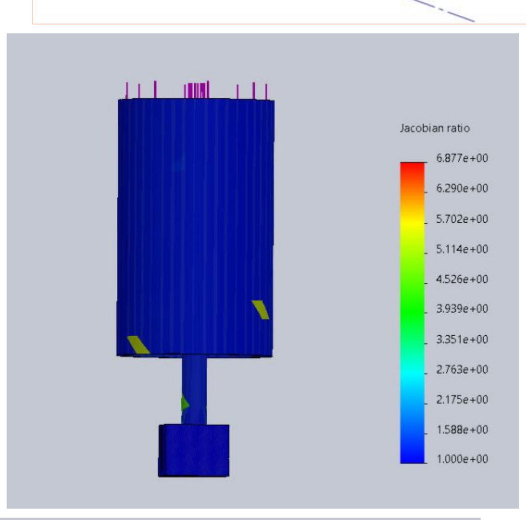
** co-efficient of friction for piston and volumetric efficiency of flow generator is ignored due to use of graphite piston/graphene coatied piston and non-continuous fluid flow, no temperature change and moderate operating pressure respectively.

Table 5: Equations Used for Calculations

Piston Area =	π·(Cylinder Diameter/2)^2
Estimated Force =	(Pump Pressure·Piston Area)/Gravity Acceleration
Estimated Torque =	Estimated Force·Torque Arm







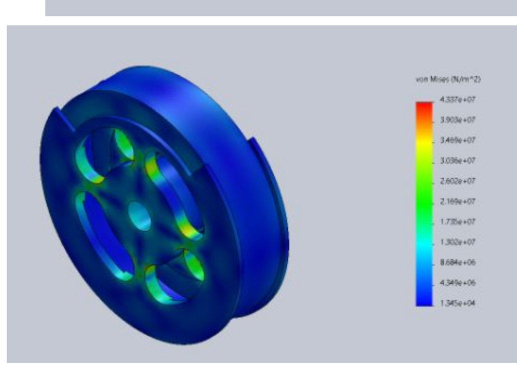


Figure (c) and (d): Final iteration of prosthetic CAD model used for simulations (left), cross-section of prosthetic design (lower left)

Figures (e), (f), and (g): kinematic drawing of prosthetic (top); FEA fatigue tests on piston-cylinder (middle) and output pulley (bottom), which are main moving components

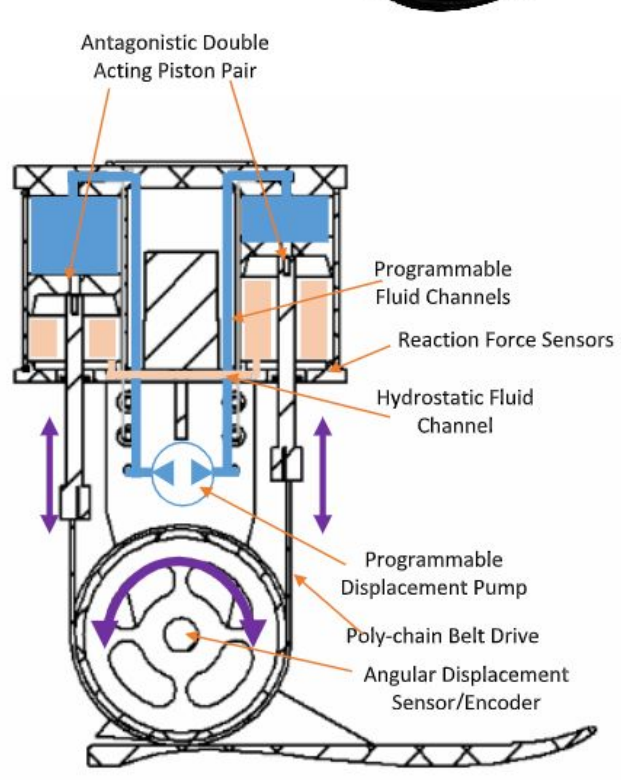


Table 6: Comparison of Pump Types

	Reference Data	Multi-Channel Peristaltic Flow Generator/Pump	Integrated External Gear Flow Generator
Target Output Torque Nm)	50	67	67
Continuous Current (A)	10	3	3
Required Flow Rate (ml/min)	6600	2200 x 3	1000
Required Motor Speed (rpm)	NA	1260	5000
Continuous Pressure (PSI)	NA	125	400
Motor Type	BLDC Iron core w/ multi-stage planetary gear and belt drive	BDC+Planatory	DD-Iron core BLDC

The SFS actuator strives for **days**, not **minutes** of use.

Table 8: 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

Table 7: Breakthroughs and Novelties

Novelty	Description
Efficient Energy Transmission	· Loss-less fluid power transfer: low-friction piston seal for near-zero stiction, achieves > 95% efficiency · No valves make it higher efficiency than state-of-art EHA · Shorter fluid channel to eliminate fluid flow resistance · High-efficiency fluidic actuator suitable for limited-motion, antagonistic double-acting cylinder pair · Cost-effective, modular, and lightweight linear-to-rotary conversion: high-efficiency toothed-belt drive capable of wide range of joint parameters
Integrated Fluid Flow Generator	Positive displacement pump is integral to actuator; multi-channel peristaltic pump for low speed or external gear pump for high speed (designed as part of the actuator eliminating seals, tubing, and connectors)
Intelligent Fluid Flow Generation	Multi-stage control strategies to achieve a programmable fluid flow as a function of actuator position, speed, and force/torque
Lower Battery Power Demand	PM motor is used only during motion to generate fluid flow to accumulate hydrostatic force as energy storage mode within the cylinders chambers. Eliminates use of iron core motor and avoids iron losses. Motor torque is isolated from joint torque so operates at lower power demand.
Smart Technology	Provides options and platforms to adopt AI and ML to achieve proprioceptive control without any additional sensors or complex mechanisms

Conclusions

- Data from empirical study, proof-of-concept tests (last year's work) and literature research effectively utilized to formulate the theoretical model (Table 4) 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
  - Sources of error from subject testing:
    - Subject fatigue over the course of testing
    - Load cells calibrated all at once, meaning accurate measurements only from central region of force plate
- Identified efficient component combinations, specifications and performance envelops through literature research and mentors' prior-art knowledge
- Ankle-specific actuator parametrization was done keeping normal joint range, torque, and speed as the target specifications
  - Sizing, weight and scalability for pediatric to adult form-fit as the design variables used for first version of CAD modelling
- 98-99% efficiency of piston, belt drive and 90% for fluidic pumps have been considered (Casey)
- Static force/pressure/torque FEA simulations on SolidWorks identified fatigues on corresponding components (examples: Figures (f) and (g))
  - 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
  - Current model (Figure (c)) has 1.7 kg total mass, including battery and covers. The bulk of mass is from the foot and top connector pending optimization.
- The flexibility of providing larger joint ranges (for knee joints) with the same design architecture timing belt transmission was chooses and was ratio was validated through motion analysis (>98% efficiency ("Timing Belt Advantages & Disadvantages | Pfeifer Industries"). Belt drive has the additional advantage of providing compliance which is being designed to provide dynamic force sensing upon ground contact.
  - Previous rocker arm version tested during proof-of-concept phase had issues with loss from friction as well as integrity
- Total scope of work has established that
  - Functionality of actuator: can easily scale up and down to accommodate user need
  - 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 8 shows estimated cost to be $1800, much less than other costs
- **Impact:** proposed actuator design theoretically proven 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.

Future Work

- Mathematical simulation of the actuator controller to validate the power consumption, control bandwidth, and force sensing as a function of frequency response.
- Assemble prosthetic prototype
  - Source components, manufacture parts and build functional prototype
  - Design and build test set-up for prototype
    - Fine-tune actuator controller
    - Validate functionality and power consumption performance under various usage demand
- Design customizable brace attachment
- Validate efficacy of proprioceptive control, self learning and adaptive control performance to build most advanced prosthetics
- Design and integration of myoelectric sensors for controlling through muscle
- Explore options of energy-harvesting
  - Technologies like triboelectric and/or kinesthetic energy harvesting
  - Support graphene supercapacitors capable
    - In turn support low power density battery pack

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