A Hydraulic Powered Ankle-Foot Prosthesis with Adjustable Nonlinear Stiffness

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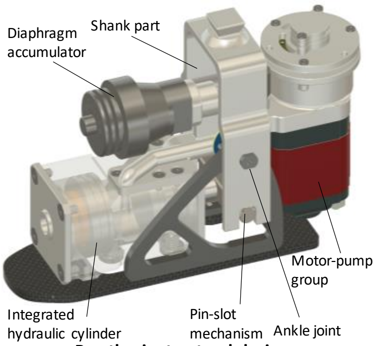
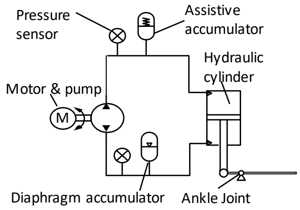
INTRODUCTION

- Hydraulic systems have been used in prosthetics, primarily relying on damping to offer support, absorb shocks, and enhance biomechanical performance[1,2]. However, elastic elements outperform damping elements in energy efficiency[3] and are better suited for the design of compact powered prosthetic feet.
- This study presents a novel hydraulic-powered ankle-foot prosthesis that uses the stiffness of hydraulic components to realize serial elastic actuation (SEA). This stiffness behavior replicates the ankle's quasi-stiffness and enables tunable stiffness, thereby improving walking efficiency.

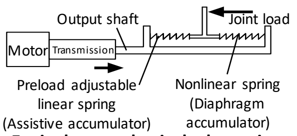
METHODS



Prosthesis structural design



Hydraulic schematic



Equivalent mechanical schematic

Actuation & Mechanics

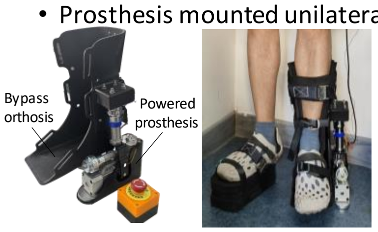
- Hydraulic cylinder with pin-slot mechanism
- Diaphragm accumulator provides nonlinear stiffness
  - — Achieved a Series Elastic Actuator (SEA)
  - — Stiffness tunable via preload adjustment

Control Strategy

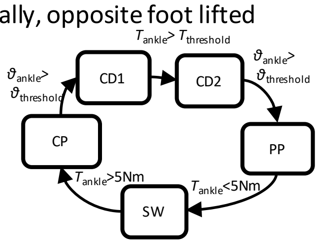
- **Stance phase**
  - — Segmented admittance controller
  - — Switched via a finite state machine
  - — Designed for bodyweight 75 kg, 1 m/s walking
- **Swing phase**: Position control

Experimental Setup

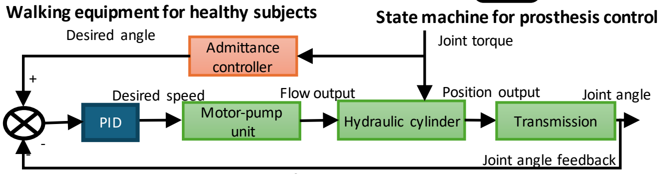
- Bypass orthosis simulating transtibial amputation
- Prosthesis mounted unilaterally, opposite foot lifted



Walking equipment for healthy subjects



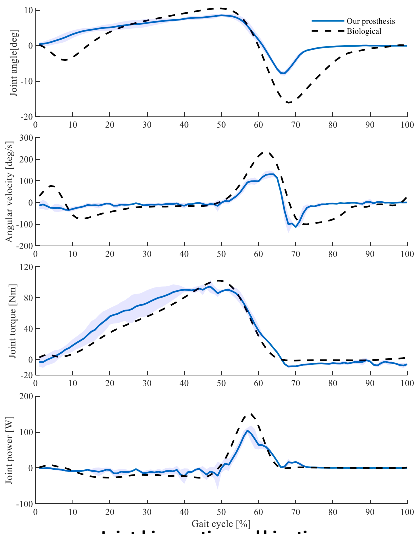
State machine for prosthesis control



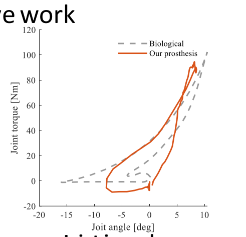
Admittance controller for the walking experiment

RESULTS

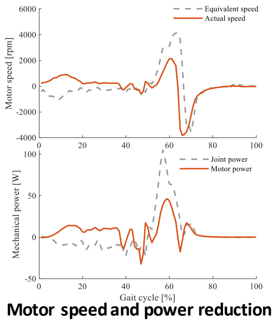
- **Kinematics & Kinetics**
  - – Joint motion and torque patterns aligned with healthy ankle
  - – Adequate support, push-off and foot clearance
- **Output Performance**
  - – Peak torque: 98 Nm (vs. human 103 Nm)
  - – Range of motion: [-9°, 9°] (vs. human [-15°, 10°])
  - – Peak angular velocity: 146°/s (vs. human 230°/s)
  - – Peak power: 112 W (vs. human 150 W)
  - – Net positive work: 6 J
- **Energy Efficiency**
  - – Diaphragm accumulator reduced:
    - Motor peak power by **53%**
    - Motor peak speed by **48%**
  - – Achieved SEA, and enabled spring-like actuator behavior
- **Advantage over Other Devices**
  - – Outperforms existing powered hydraulic prostheses in mass, peak power, and net positive work



Joint kinematics and kinetics



Joint impedance



Motor speed and power reduction

Comparison of typical prosthetic parameters

	[1]	[2]	Our design
Mass (kg)	2.2	3	1.8
Peak Torque (Nm)	80	81.9	98.7
Peak Power (W)	60–85	57.9	112
Net Positive Work (J)	--	4.7	6
Range of Motion (°)	21	16.7	28

CONCLUSION

- The proposed hydraulic ankle-foot prosthesis demonstrates biomechanical performance close to a healthy limb in joint torque, power, and quasi-stiffness.
- Its compact design, lightweight, and power output outperform comparable hydraulic powered prosthetic feet. Demonstrates strong potential for practical, energy-efficient lower-limb assistance.
- Future work will explore:
  - — Performance across various gait modes
  - — Implementation of real-time variable stiffness control

[1] Tian Yu, Andrew R Plummer, Pejman Iravani, Jawaad Bhatti,Saeed Zahedi, and David Moser. The design, control, and testing of anintegrated electrohydrostatic powered ankleprosthesis. IEEE/ASME Trans-actions on Mechatronics, 24(3):1011–1022, 2019.
[2] Xinyu Tian, Shaoping Wang, Xingjian Wang, Dengpeng Dong,and Yuwei Zhang. Design and control of a compliant electro-hydrostatic-powered ankle prosthesis. IEEE/ASME Transactions on Mechatronics,27(5):2429–2439, 2021.
[3] Mahdy Eslamy, Martin Grimmer, Stephan Rinderknecht, and An-dre Seyfarth. Does it pay to have a damper in a powered ankle prosthesis? a power-energy perspective. In 2013 IEEE 13th International Conferenceon Rehabilitation Robotics (ICORR), pages 1–8. IEEE, 2013.

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