Modular Low-Cost 3D-Printed Exoskeleton for Worker Injury Prevention

Robotics and Intelligent Learning Lab

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Introduction

- The goal of this project was to create a low-cost 3D printed exoskeleton with a high torque density actuator which could be used by worker in industries that have long term health effects associated with there work.
- This exoskeleton system was designed to be easily 3D printed to minimize cost as well as be modular for specification to the desired job. Materials for the gearbox and joints were chosen to be durable and stress resistant.
- The exoskeleton focuses on injury prevention in the shoulder, lower lumbar, and lower extremities
- An impedance controller was designed to provide intuitive load compensation to users, reducing physical strain across a variety of movements.

Upper and Lower Limb Exoskeleton Systems

- The exoskeleton was designed to be modular in two pieces, a module for lower limb assistance and a module for upper limb assistance.

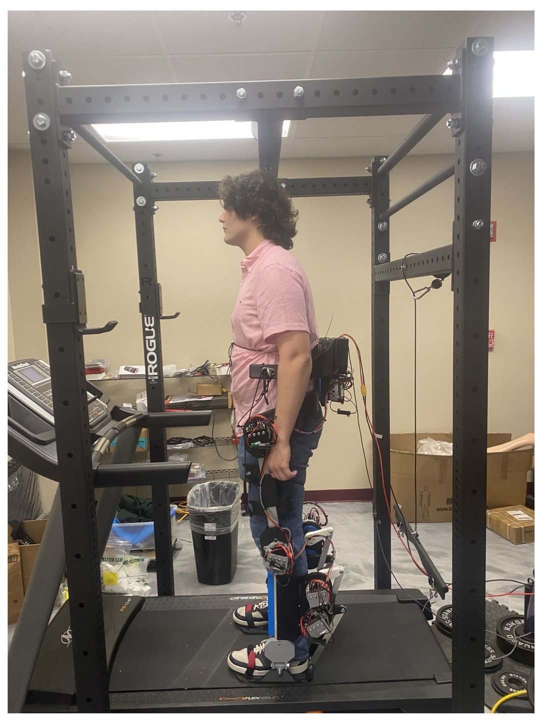

Figure 1: An individual wearing the full lower limb exoskeleton

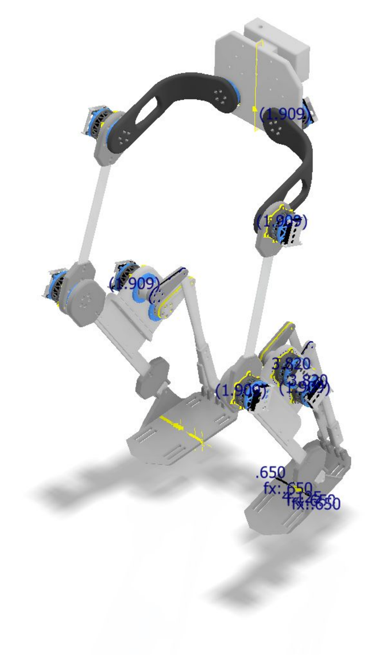

Figure 2: CAD model of the full lower limb exoskeleton

- The lower limb module of this exoskeleton was designed to have ten degrees of freedom (DOFs), attempting to align with the twelve natural DOFs from the hip down while other lower limb exoskeletons have limited lower DOF such as ALICE exoskeleton Cardona[1] and Dežman [2]
- The ankle uses a unique design, that being two four-bar linkages that allow for dorsiflexion and plantar flexion of the foot.
- The lower limb module maintains a weight of approximately 32 pounds without battery storage and costs ~$4000 in material cost. Battery storage will add an estimated 7.0 lbm to the total mass of the exoskeleton.

Figure 3: CAD Model of the novel 2 DOF ankle

- The model is similar to ALICE exoskeleton Cardona[1] at the hip and Dežman [2] but incorporates all their degrees of freedom in one system.
- The design uses two heim joints at the end of each lever arm, creating a four-bar linkage with the u-joint present at the ankle enabling eversion/inversion mobility during gait as opposed to only dorsi/plantar flexion seen in exoskeletons at the ankle.

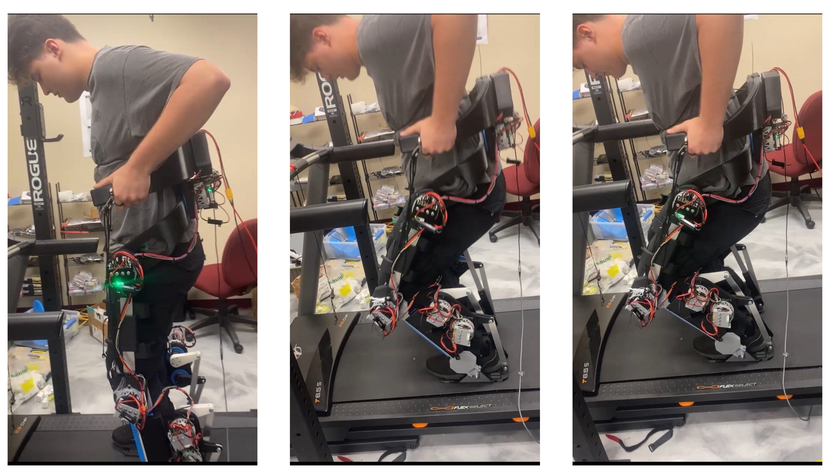

Figure 4: Impedance controller test trial

- Screenshots of an individual performing a squat motion can be observed in Figure 4, showing the lower limb exoskeleton's range of motion.

Figure 5: Test bed for the upper limb exoskeleton

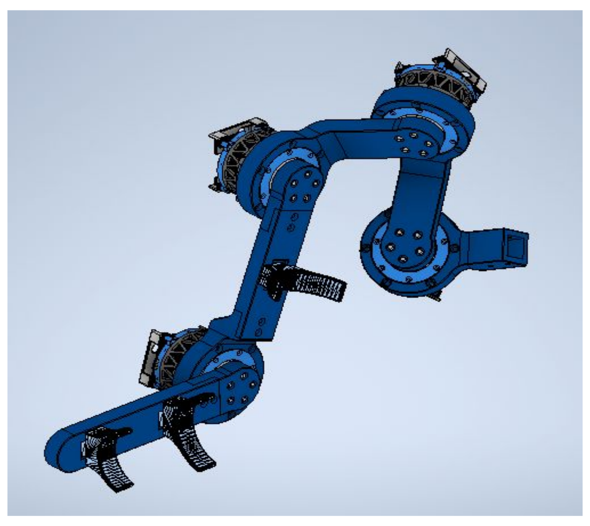

Figure 6: CAD model of upper limb exoskeleton

- The upper-limb module of this exoskeleton was designed to have four DOFs: shoulder flexion/extension, shoulder abduction/adduction, shoulder pronation/supination, and elbow flexion/extension.
- A single arm of the upper-limb module maintains a weight of 8.9 pounds and costs ~$1500 in material cost

3D Printed High Torque Density Actuator Design

- The exoskeleton uses 3D printed Cycloidal gearboxes with a 13:1 reduction similar to the one used in Gonzalez[3]
- The cycloidal was selected for its high torque density while being manufacturable using 3D printing techniques. This being due to the cycloidal cut of the gear not being easily susceptible to shear.
- The cycloidal utlized by the exoskeleton differs slightly from that in Gonzalez[3] with the main crankshaft and components in contact with the motor being printed in polycarbonate, the rollers on the fixed ring pins being printed in durable UV-cured resin, and all other components printed in PLA+.

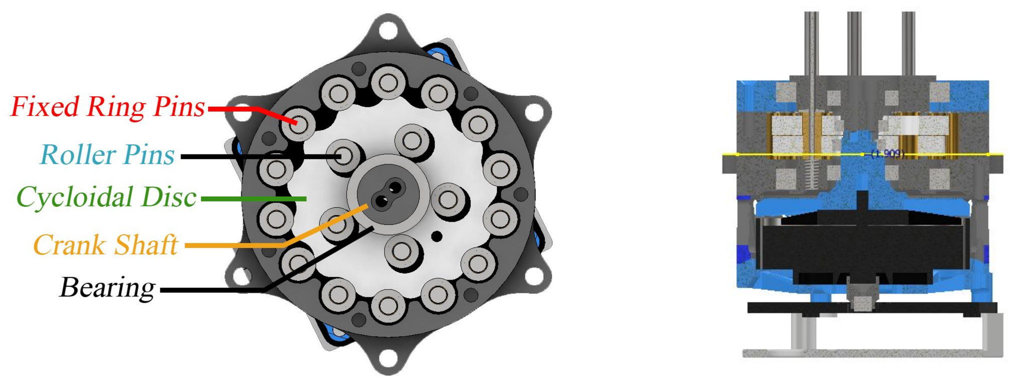

Figure 7: CAD images of a cross section of the cycloidal gearbox to show the cyclodial gears and the motor construction

- The stall torque for the gearbox is directly influenced by the motor selected has safe current for the motors at 36 A.
- The maximum stall torque was found to be 36.7 N-m, pulling a peak current of 44.4 A. A soft current limit of 36 A is used for regular motor operation.
- Figure 8 shows the torque tracking with high precision.

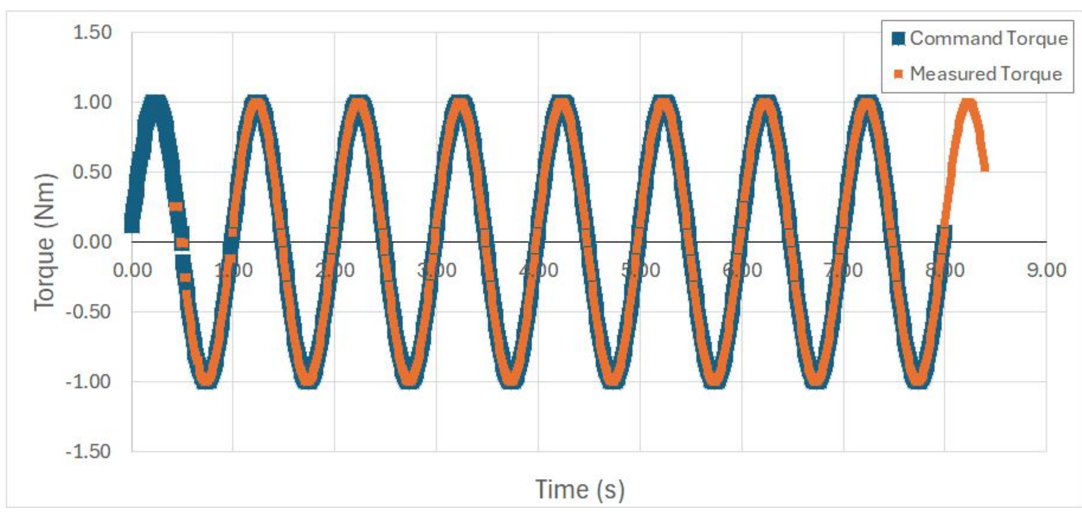

Figure 8: Torque tracking results for a 1 Hz sine wave of 1 Nm amplitude

- The cycloidal actuator was compared to the ultralow impedance exoskeleton (ULIX) actuators by T. Chen[4] and the AK90 motor, a commercial off-the-shelf motor.
- These were selected due to the ULIX actuator being a series elastic actuator and the AK90 due to its wide usage in larger robotics platforms.
- The peak torque density is comparable to the AK90 and ULIX actuators with a significantly lower cost.

	ULIX	AK90	Our Cycloidal Drive
Nominal torque Density (Kg/Nm)	15.3	18.75	20.36
Peak torque Density (Kg/Nm)	38.8	50	47.93
Mass (Kg)	0.9	0.960	0.766
Bandwidth (Hz)	3.7	NA	~60
Backdrivability torque (Nm)	0.5	0.8	1
Cost ($)	Unspecified	798.90	375

Software

- The exoskeleton utilizes ROS2 Humble as the primary software framework, allowing for complex, modular behaviors.
- Real-time control of the actuators is achieved using the official ODrive ros2_control package.
- Actuators can be driven with position, velocity, or torque control, and provide position, velocity, and torque feedback.
- An impedance control algorithm as seen in Figure 9 is implemented to assist users in holding desired positions and completing squatting to standing movements.
- The impedance controller can detect human motion intention and generate a reference torque during the squatting movement.

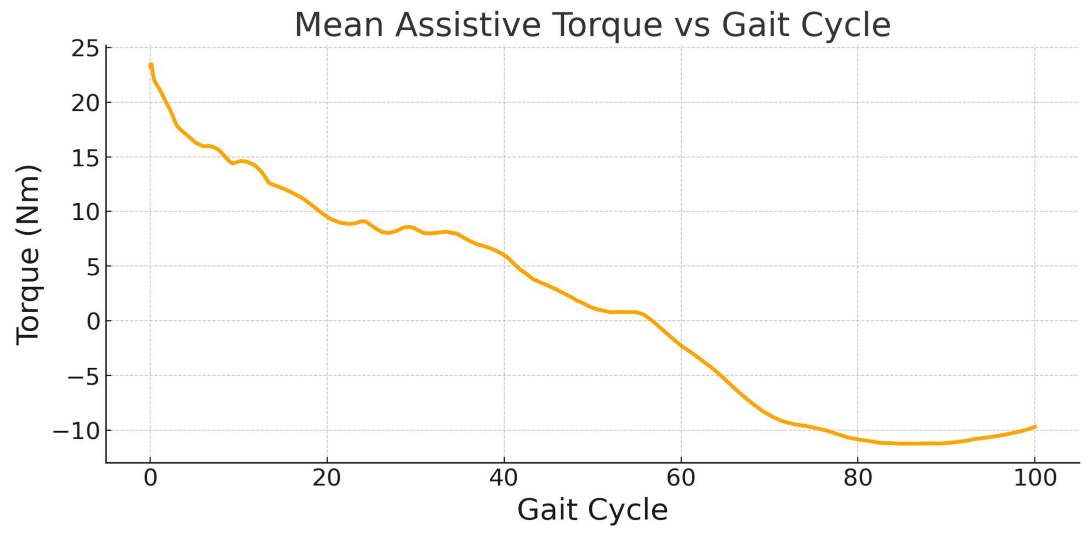

Figure 9: Knee Joint Assitive Torque vs. Gait Cycle as the user performs a parallel squat to stand motion

- The peak torque assistance is approximately 24.5 N-m, occurring at a parallel squat position.
- The ODrives contain a lower-level PID structured controller for the position, velocity and torque control commands.
- The control structure can be seen in Figure 10 with the torque exerted by the motors to aid in gravity compensation.

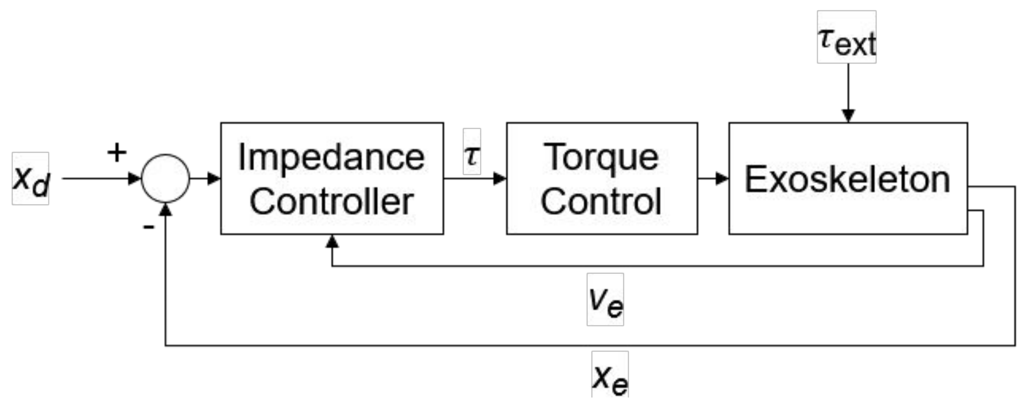

Figure 10: Impedance Control Block Diagram

Conclusion and Future work

- This exoskeleton offers a low-cost platform for injury prevention with an actuation system that delivers sufficient assistive torque to aid in industrial processes.
- The upper-limb and lower-limb module offer a combined 18 degrees of freedom of assistance across the lower and upper extremities.
- The impedance controller offers a simple, inuitive control scheme that can aid users in lifting and squatting.
- Future work will focus on creating a generalized control scheme which can successfully assist users in a wide variety of tasks, as well as comparing biological effort with and without the exoskeleton.

References

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