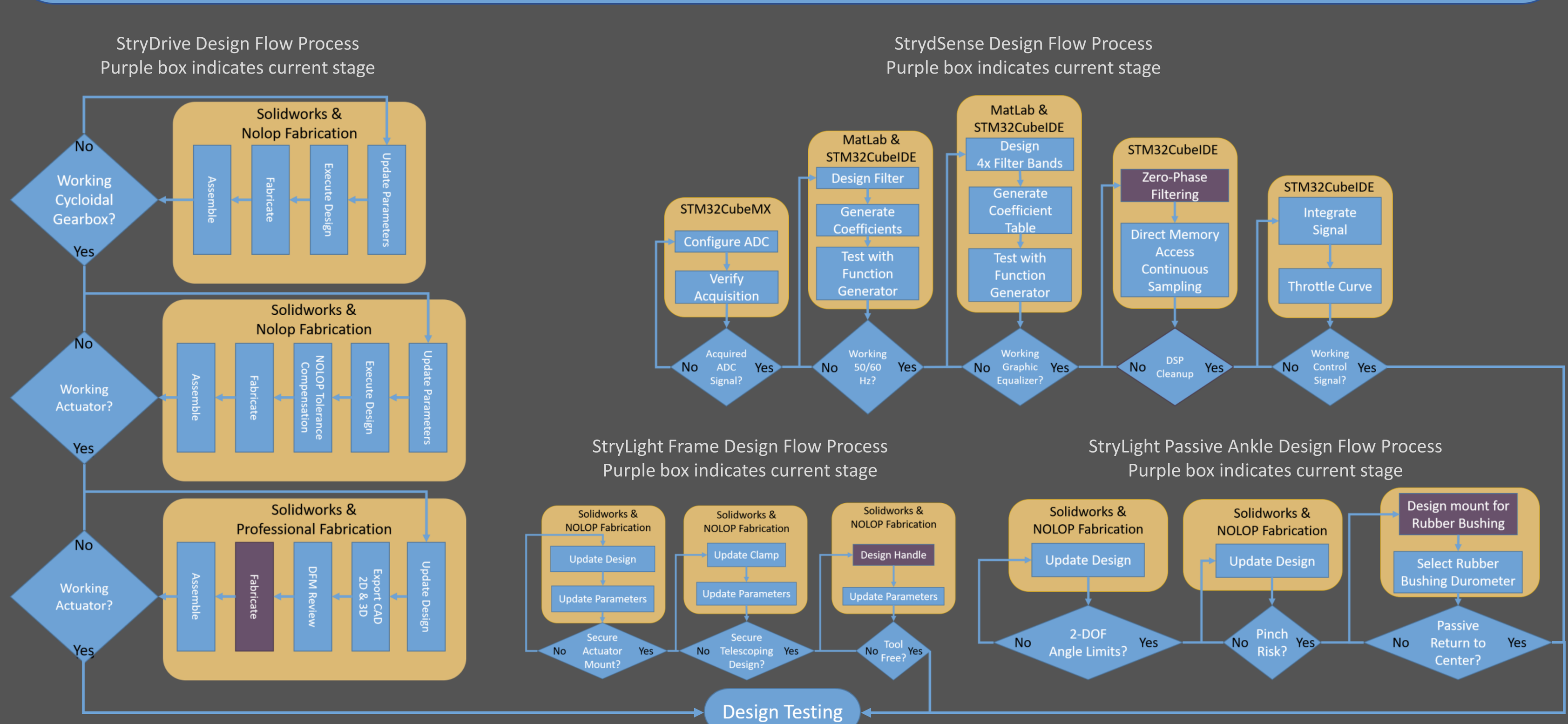
Introduction and Background:

Exoskeletons augment human capabilities and performance in specific tasks. Unlike prosthesis, the main objective is to increase the power of the user by mirroring their motion and providing assistance on demand. Exoskeletons are appealing where the presence of a human operator is both preferred and critical. Popular applications target the mobility challenges of elderly and spinal cord injury patients as well as promoting stroke recovery. Styrdr is divided into three specific aims which feature two primary design components. Strydr differs from existing solutions and research because of its brushless motor implementation and balanced cycloidal gearbox.

- Approximately 10% of adults between their sixties and seventies develop a gait disorder which balloons to excess of 60% of adults older than 80 (Pirker & Katzenschlager, 2017). The structural support and enhanced motion control help overcome age related mobility challenges such as achieving sufficient foot clearance over obstacles.
- Stroke patients, depending on the severity of their injury, may require months to years of training to regain muscular control. Per annum, there are 191,000 new patients in Japan, 795,000 new patients in United States, and 200,000,000 new patients in China (Zhang et al., 2017). Although parallel limb exoskeletons are primarily strength augmentation devices, they can also provide resistance to motion for training and rehabilitation.
- Paraplegia affects the mobility of approximately 288,000 individuals within the United States with an addition 17,700 new patients per year. The lifetime costs for individuals injured at age 25 and 50 are in excess of one million dollars (*Spinal Cord Injury Facts and Figures at a Glance*, 2017).
- Applications in industrial safety may also be considered a preventative healthcare application. 70% of workplace injuries are unreported within the United States (Fagan & Hodgson, 2017). 28.2% and 36.3% of the 2.8 million reported, non-lethal injuries in the private and retail sectors are associated with overexertion. 30.7% and 38.4% of reported injuries are associated with sprains/strains/tears and 15.9% and 16.1% are associated soreness/pain (Bureau of Labor Statistics, 2019).

Engineering Design Process

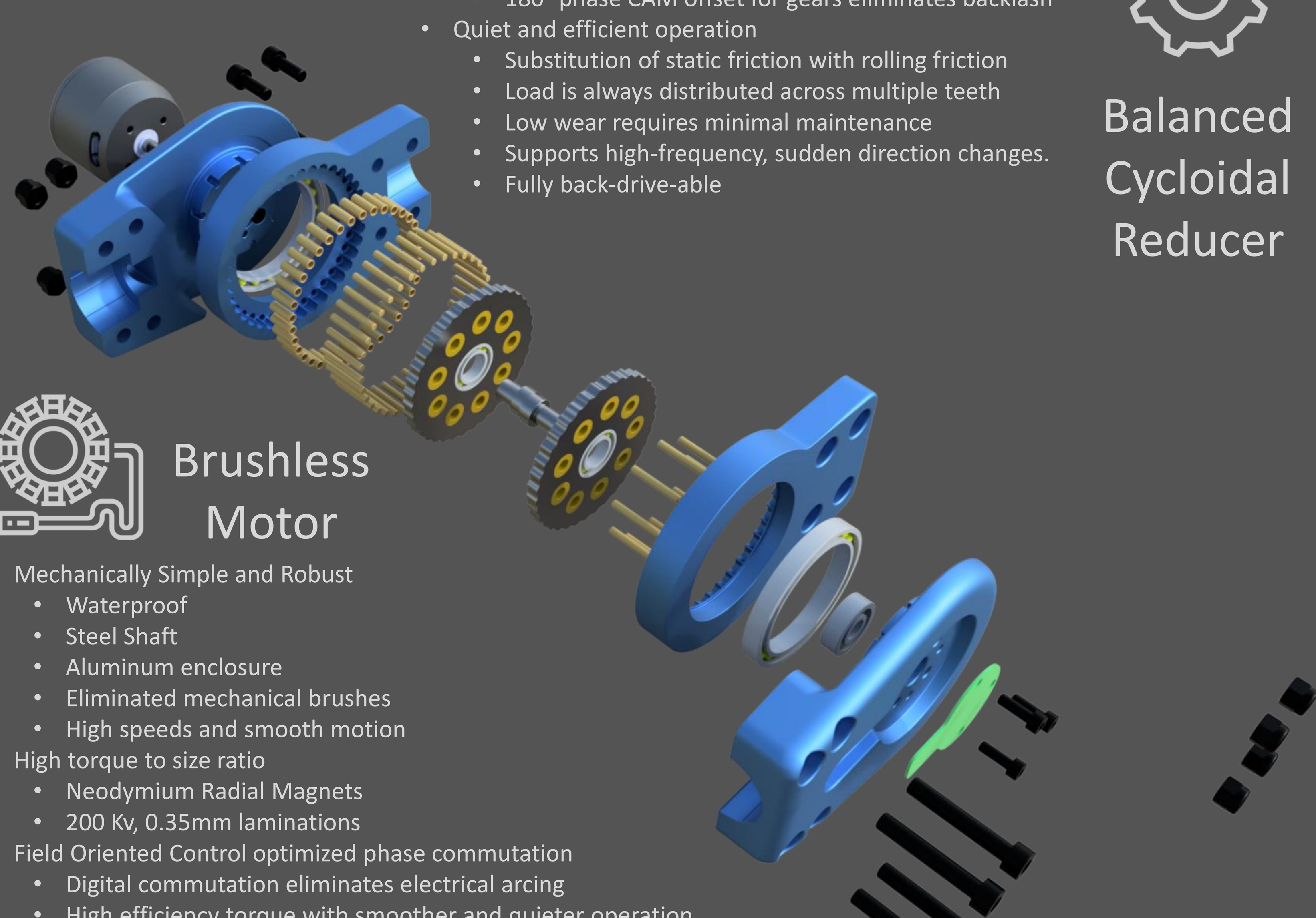


StryDrive™

StryDrive™ is a universal actuator for hips and knees that delivers high-efficiency lifting and holding torque in a discreet design with accurate position, velocity, and torque sensing. Cycloidal gears are unstandardized and cost thousands of dollars from industrial robot manufacturer catalogs. A parametric Solidworks model was iteratively designed through a combination of 3D printing and laser cutting fabrication and tested for rotational smoothness. Experiments with a 3D printed gearbox are limited by the power required to generate maximum torque and the softening point of the plastic components. The final version, manufactured with tolerances of 0.01mm from a combination of 6061-T6 aluminum and JIS S45C Steel, scheduled for final verification experiments and performance measurements was delayed due to COVID-19.

Balanced Cycloidal Reducer

- 36:1 Single-stage, balanced gearbox
  - 6061-T6 aluminum and JIS S45C Steel (±0.01mm precision)
  - 180° phase CAM offset for gears eliminates backlash
- Quiet and efficient operation
  - Substitution of static friction with rolling friction
  - Load is always distributed across multiple teeth
  - Low wear requires minimal maintenance
  - Supports high-frequency, sudden direction changes.
  - Fully back-drive-able

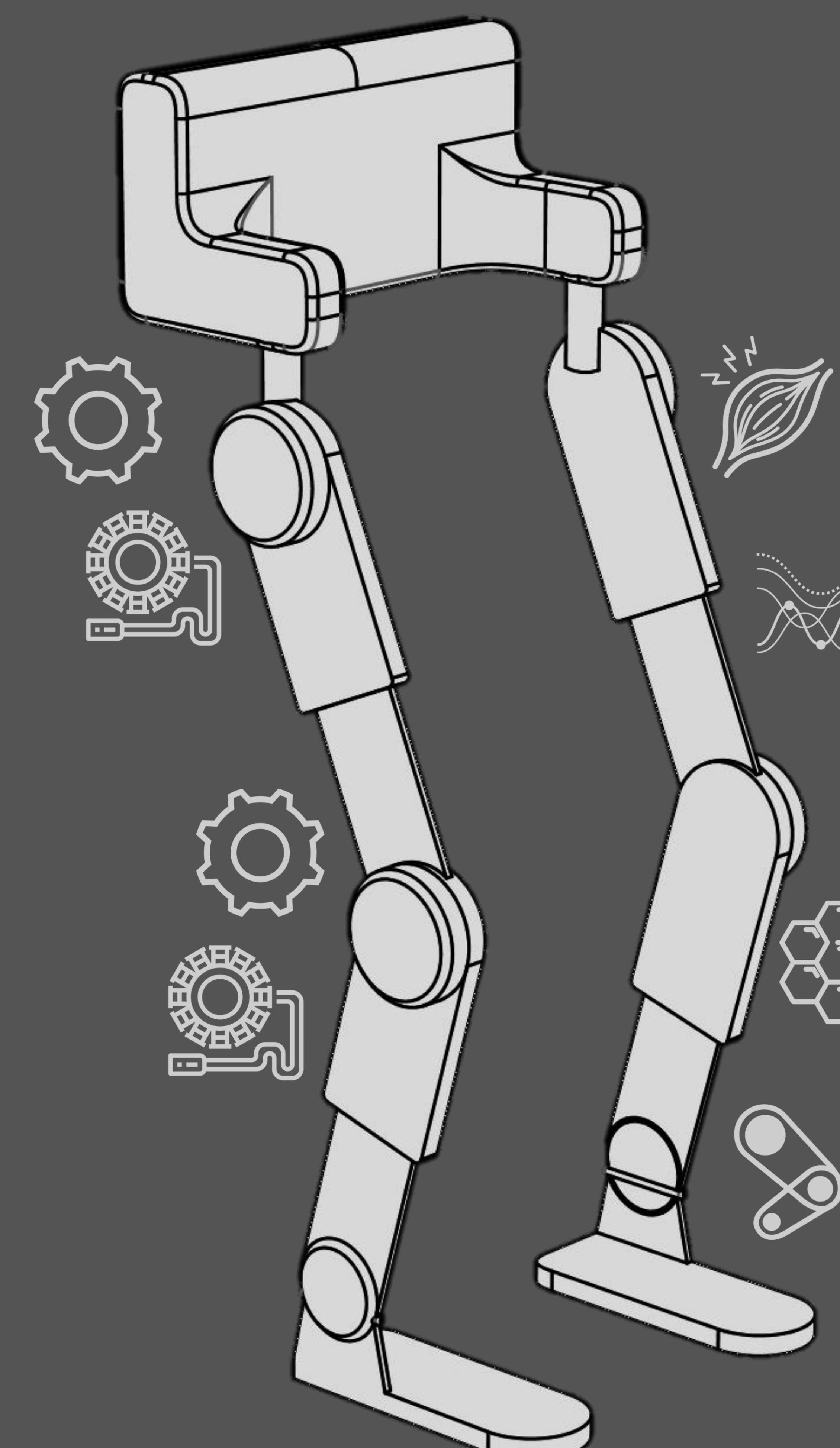


Brushless Motor

- Mechanically Simple and Robust
  - Waterproof
  - Steel Shaft
  - Aluminum enclosure
  - Eliminated mechanical brushes
  - High speeds and smooth motion
- High torque to size ratio
  - Neodymium Radial Magnets
  - 200 Kv, 0.35mm laminations
- Field Oriented Control optimized phase commutation
  - Digital commutation eliminates electrical arcing
  - High efficiency torque with smoother and quieter operation
    - Minimize radial force vector and maximize tangent force vector
  - Position, velocity, and torque estimates without additional sensors

Discussion

- Absence of standardized design protocols and parameterizations required an iterative design process to identify parameters critical for the proof of concept StryDrive.
  - Identification and compensation of manufacturing defects specific to the available equipment and fabrication processes was critical for distinguishing design errors from fabrication errors.
- Solidworks is unable to apply a CAM mate to a self-intersecting equation-driven spline. This greatly interference, motion, and stress simulations.
- Embedded hardware platform selection required serious consideration of system bus design and clock speed stability.
  - Initial hardware designs suffered from a 6% inaccuracy in system clock speed which fluctuates the ADC sampling rate between 940 and 1060 Hz. This affects both data input and processed DSP output.
- MATLAB does not provide explicit documentation for the synthesis, formatting, and implementation of filter coefficients in ARM processors.
  - Substantial background research into the implementation of both the generating MATLAB functions and the DSP API ARM functions was required.
- The integrated Direct Memory Access controller can perform the buffering and transfer of data from peripherals to RAM and vice versa to eliminate CPU usage associated with that task.
- Finite Element Analysis does not take into consideration infill and shell thickness parameters introduced by the slicer programs prior to 3D FDM printing resulting in mechanical performance discrepancies in 3D printed components.



STRYDR

Strydr.co

Tufts Biomedical Engineering Senior Capstone
Kenneth Meyerson, Class of 2020

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Conclusions and Future Work

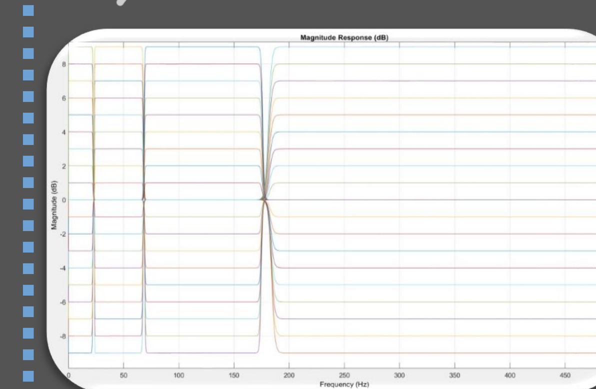
- The fifth and final plastic prototype of StryDrive handles sudden and high frequency direction changes smoothly and quietly indicating that the refined parameters are sufficient for transfer and fabrication from metal to begin design testing.
  - An October 2019 publication featured an unbalanced cycloidal reducer in a lower limb exoskeleton and reported a 29% average increase in current consumption for unbalanced cycloidal powered joints whereas planetary gear powered joint in the same exoskeleton demonstrated average increases of 62 and 112% (Minchala et al., 2019).
  - Torque efficiency and service life and shall be determined through cyclic and static testing with a weight of 15 Kg at 1/3rd meter with disassembly and visual inspection at cycle milestones during cyclic fatigue testing.
  - Redesign of the StryDrive into an integrated motor and gearbox simplifies its application in future designs. The current/torque ratio shall be linearized by increasing the diameter of the motor and integrating a lower radio cycloidal reducer (6:1 vs 36:1) into the brushless motor shaft assembly.
  - The determination of the optimal application of the StryDrive must be pursued.
    - The high-frequency, sudden direction change performance and low-profile design are an interesting solution for increasing the portability of Bowden cable-based exoskeletons.
- StrydSense demonstrates the core implementation challenges of EMG signal acquisition and digital signal processing, providing the framework required for the continued expansion and development of the control system.
  - Phase shifts introduced by IIR BiQuads will be corrected with Zero-Phase filtering, delayed due to COVID-19.
  - Configuration of the Direct Memory Access controller to optimize CPU usage was delayed due to COVID-19.
  - Ramped control signals to correlate the intensity of flexion with desired joint actuation was delayed due to COVID-19.
  - EMG wavelet analysis and machine learning can be leveraged to recognize signals specific to users to provide more intuitive controls.
- StrydLight demonstrates the core implementation challenges of a design compatible with a wide range of users.
  - Frame length adjustment did not mature to feature tool-free adjustment due to COVID-19 delays.
  - Ankle joint does not passively return to center due to COVID-19 delays.
  - Cylindrical elements are convenient for designing telescoping systems but are less rigid than rectangular elements.

StrydSense™

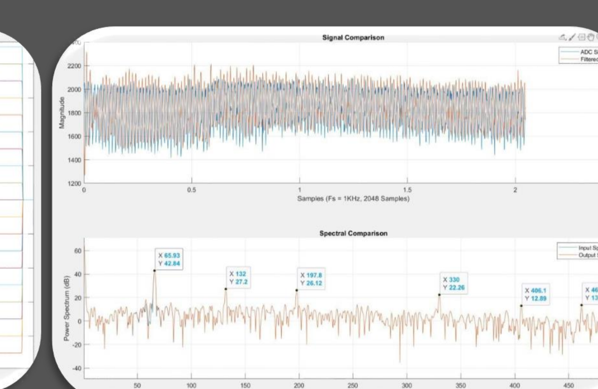
StrydSense™ acquires and processes electrical activity from muscle groups in parallel limbs to generate a control signal for the StryDrive. Marketed exoskeletons solutions demonstrate surface EMG control and StrydSense implements the core techniques behind this technology. The Analog Front End amplifies biopotentials and a local microcontroller provides digital signal processing to generate a control signal for StryDrive. An off-the-shelf AFE was used to minimize cost, time constraints, and troubleshooting. MATLAB was used to design digital filters later ported to the microcontroller using the STM32CubeIDE. StrydSense leverages the ARM CMSIS abstraction layer to apply hardware accelerated DSP functions. Functionality was verified by comparing the output of a prerecorded signals processed in MATLAB and on the microcontroller. Feature beyond core scope were not implemented due to COVID-19 delays.

EMG Sensor

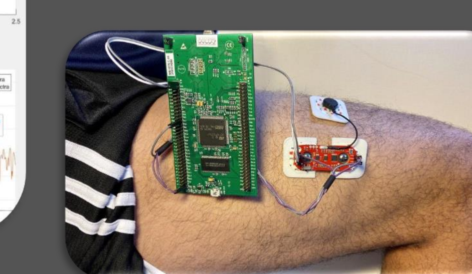
- Principles Electrical engineering
  - Amplifier Input Impedance
  - Common Mode Rejection Ratio
- Principles of electrophysiology
  - Low Frequency EMG Source signal
  - Non-invasive design requirement eliminate needle electrodes
  - Non-polarizable Ag/AgCl electrodes behave resistively making them better suited for low frequency biopotential recordings.



4-Band Graphic Equalizer to apply negative gains to noise and positive gains to EMG rich regions.



Sampled EMG signal and filtered output
60 Hz filter + [0,0,0,0] Gain EQ



STM32F429-DISC1 and Advancer AT-04-001 EMG AFE

Digital Signal Processing

- Simplified Analog Front End bill of materials
- Embedded code execution with hardware accelerated DSP functions
- Programmable filters
  - 50 and 60 Hz power-line filter
  - Equalizer to attenuate noise and apply gains to select frequency bands.

StrydLight™

StrydLight™ is a tool-free, one-size-fits-all composite frame that provides a load bearing structure and physical interface between the user and exoskeleton. The StrydLight frame was developed through a combination of mechanical engineering calculations, Solidworks, 3D printing, hacksaws, and sewing machines. These designs were verified through qualitative assessments of comfort and impact on range of motion. Features beyond core scope were not implemented due to COVID-19 delays.

Carbon Fiber Frame

- Carbon Fiber Tubes
  - Reduces user fatigue and rotational inertia.
  - ~1.5x the strength of equivalent 1060 aluminum parts for 20% of weight.
- Telescoping Design
  - Compatible with a wide range of users
  - Tool-Free length adjustment
- Comfortable
  - Quick and Accessible interface with user
  - Magnetically aligned, sliding lock clasp.
  - Washable pad between the user and frame

Passive Joint

- Transfer loads from the exoskeleton to the floor during testing.
- Passive, elastic bushings return the joint to center (Unimplemented due to COVID related delays)

StryDrive V5 (Green/Blue), StrydLight Telescoping Clamp (Grey), StrydLight User Interface (Red with Black Strap), Passive Ankle Joint (Purple/Red)