Soft Robotics Variable Stiffness Exo-Musculature, One-To-Many Concept, and Advanced Clutches

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Outline

• Introducing Exo-musculatures
• Novel Actuation Mechanisms: “One-to-many”
  • Motivation (limitations of conventional approaches)
  • Architecture
• Demonstration of clutch mechanism that could provide:
  • Variable stiffness
  • Elastic potential energy storage
Soft-Robotics Exo-Musculature (SRE)
Soft-Robotics Exo-Musculature

- Actuation Package
- Transmission
- Sensing
- Control
Soft-Robotics Exo-Musculature

Minimum Cable Tension

\[ x_2 = x_1 + \frac{y_2}{x_L} (y_1 - y_2) \quad \Rightarrow \quad x_2 = 0.136 \text{ m} \]

Minimum Force on Joint

\[ x_2 = \frac{x_1 + \sqrt{x_1^2 + 4y_2(y_1 - y_2)}}{2} \quad \Rightarrow \quad x_2 = 0.104 \text{ m} \]

- Minimize the overall cable tension
- Minimize the forces applied into the shoulder joint that result in no torque

The mean distance from the greater tubercle to the proximal and distal insertion of the deltoid muscle in humans is \(0.061\) m and \(0.158\) m respectively (Morgan 2006)

*Example of learning on human biomechanics from robotics!*
Soft-Robotics Exo-Musculature

• Can be successfully actuated with biologically-realistic forces counteracting gravity

• Arm angular position can be accurately estimated with inexpensive sensors

• Control time delays are smaller than biological ones

• Adaptive control system can successfully address anatomical variations and misalignments

*Joint work with collaborators at Harvard University and UPM
Demo with one of the first Exo-Musculature prototypes (Dec 2011) for post-stroke rehabilitation. Shoulder brace (right) attached to a mannequin arm with added weights tele-operated by Professor Popovic.
Soft-Robotics Exo-Musculature

• To mimic human musculature requires a very large number of independently actuated degrees of freedom.
• About 400 skeletal muscles in the body
  — each one contains 100 or more motor units
Motivation for *One-To-Many* approach

To create a fully mobile, wearable system:

- Achieve Fine and Variable Stiffness in biologically-inspired fashion
- Low weight
- Cost effective
- Minimize number of electric motors
- Maximize number of independently actuated motor units
- Emulate Human Dexterity
The **One-To-Many** Control Results: Variable Stiffness

Simple Arm Model: pair of antagonistic muscles.

The static experiment: Arm trajectory with varied number of recruited muscle motor units.
Benefits of an Electromechanical System

The Exo-Musculature’s artificial muscles are electromechanically actuated. For applications requiring full mobility, this is more suitable than pneumatic or hydraulic actuators.

- An average human weighing 82 kg walking at 6.44 km/h burns approximately 384 nutritional calories (1.61 MJ) per hour.
- Practical achievable energy density at the motor shaft for a pneumatic system is about 40-100 kJ/kg.
- The mass of the compressed air system required for one hour of walking using a whole body exoskeleton system with same cost of transport as a human is 28-145 kg.
- A lithium battery has an energy density of 1.3 MJ/kg

![Air Tanks (23 kg)](image1) ![Lithium Polymer Battery (1 kg)](image2)
The *One-To-Many (OTM)* Approach

![Diagram showing the One-To-Many (OTM) Approach](image)
Example of the *One-To-Many* motor unit

The single motor unit consists of 3 clutches (C1, C2, C3), 2 elastic elements (E1, E2) and 1 roller R3 that takes a “muscle” fiber slack. Also shown are rollers R1 and R2 that are shared by many motor units from same or different “muscles”.

Phase 0 (C1 open, C2 open, C3 open): E1, E2 in equilibrium.
The *One-To-Many* Clutches

**Desired clutch specifications:**

- low-power
- light weight
- high-speed
- energy efficient
- robust
- provides position sensing
- can be easily miniaturized
- inexpensive
- can be easily integrated to Exo-Musculature
From Soft Robotics Exo-Musculature to One-To-Many Clutches

(A) clutch utilizing forked-roller mechanism with small stopper, (B) clutch utilizing claw/gear mechanism, (C) clutch utilizing sliding-gate mechanism, (D) electromagnetic linear clutch utilizing rollers, and (E) electromagnetic slider clutch.
Current Clutch

Consists of a DC latching solenoid and a toothed-pulley. The clutch only requires power to change states. Once state is engaged, force is held passively without energy input.
Current System
Demonstration
Thank you!