Energy efficient actuators for biomechanical applications
From accurate models to energy-efficient concepts

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Variable Impedance Actuators

- Pneumatic muscles, MACCEPA, SPEA, self-healing
- Safety
- Energy efficiency
- High torques

Cognitive and physical human-robot interaction

Coworkers for manufacturing, bipeds, social robots for robot assisted therapy, bipeds, rehabilitation and assistive exoskeletons, prostheses
Why study energy efficiency?

- Reduced energy consumption
- Longer autonomy
- Smaller drivetrain
- Smaller battery pack
- Less noise, heat production
Optimizing for efficiency

Energy efficient design can be achieved by minimizing

\[ C = \int |P_{mech}|dt \]

\[ = \int |T \cdot \omega|dt \]

(i.e. by minimizing the mechanical energy consumption)

Power flow through drivetrain

How does this relate to \( E_{elec} \)?
Experimental verification

Case study: pendulum

\[ \theta = \theta_0 \sin(\omega t) \]

Torque and mechanical power

![Torque and mechanical power graphs](image-url)
Mechanical vs. Electrical power

- High losses in powertrain
- Symmetry lost
- Simple model incorrect...

\[ P_{elec} = \frac{1}{\eta_g \eta_m} P_{mech} \]
Electrical power

Loss mechanisms / drivetrain dynamics matter!

• Gearbox: $P_{loss} \sim T \dot{\theta}$
• Motor: $P_{loss} \sim T^2, \dot{\theta}^2, \dot{\theta}$
• Friction: $P_{loss} \sim \dot{\theta}^2, \dot{\theta}$
• Controller losses: ?
• Motor inertia

Verstraten et al., *Modeling and design of geared DC motors for energy efficiency: Comparison between theory and experiments*, Mechatronics (2015)
How to improve efficiency

Two concepts

Compliance

Redundance
Rigid actuator

Load → Transmission → Motor → Controller → Power source

η = 72%  η = 88%  η = 94%
Rigid actuator
Steady state - motor

Forward drive:

\[ T_{\text{motor}} = \frac{1}{\eta_g \eta} T_{\text{load}} \quad (P_{\text{load}} > 0) \]

\[ \rightarrow |P_{\text{load}}| < |P_{\text{motor}}| \]
Rigid actuator
Steady state - generator

Forward drive:

\[ T_{motor} = \frac{1}{\eta_g n} T_{load} \quad (P_{load} > 0) \]

Reverse drive:

\[ T_{motor} = \frac{\eta_g}{n} T_{load} \quad (P_{load} < 0) \]

\[ \rightarrow |P_{load}| > |P_{motor}| \]
Rigid actuator

Dynamic applications:

\[
T_{\text{motor}} = \frac{1}{\eta_g n} T_{\text{load}} \quad (P_{\text{load}} > 0)
\]

\[
T_{\text{motor}} = \frac{\eta_g}{n} T_{\text{load}} \quad (P_{\text{load}} < 0)
\]
Improving efficiency: compliance

Bypass the lossy components
Introduce an energy storage buffer at the output!
Efficiency & Natural Dynamics

Resonance:
• $T = 0$

\[ P = T \omega = 0 \]

• At least one

Verstraten et al., *Modeling and design of geared DC motors for energy efficiency: Comparison between theory and experiments*, Mechatronics (2015)
Antiresonance

Nearly no motion! 
\( \dot{x} \approx 0 \)
Series Elastic Actuation

Antiresonance:

\[ P = T \omega_1 = 0 \]
Parallel Elastic Actuation

\[
\omega_0 \approx \frac{Mgl + k}{\sqrt{J + J_{\text{drive}}}}
\]

PEA: Max power vs. velocity and stiffness
Verstraten et al., *Series and parallel elastic actuation: impact of natural dynamics on power and energy consumption*, Mechanism and Machine Theory (2016)
Series or Parallel?
Electrical peak power

Verstraten et al., *Series and parallel elastic actuation: impact of natural dynamics on power and energy consumption*, Mechanism and Machine Theory (2016)
Series or Parallel?
Mechanical energy

Verstraten et al., *Series and parallel elastic actuation: impact of natural dynamics on power and energy consumption*, Mechanism and Machine Theory (2016)
Series or Parallel?
Electrical energy

Series

Parallel

Verstraten et al., *Series and parallel elastic actuation: impact of natural dynamics on power and energy consumption*, Mechanism and Machine Theory (2016)
Series or Parallel?

Addition of offset: \[ \theta = \theta_0 \sin(\omega t) + \theta_1 \]

Additional static torque!

- **PEA**: compensation by setting equilibrium angle
  \[ \theta_{eq} = \frac{Mgl \sin(\theta_1)}{k_p} + \theta_1 \]

- **SEA**: cannot compensate!
Series or Parallel?
With offset

Energy consumption with optimal stiffness tuning:

**Series or Parallel?**

**Series**
- Decoupling of motor and load (additional DOF) = increased **safety**
- Load force = motor force
- Extra **antiresonance** frequency (+resonance)
- Reduction of motor **speed and torque**
- Cannot cancel static torque

**Parallel**
- No decoupling of motor and load = no increase in safety
- Load pos. = motor pos.
- Shift of **resonance** frequency
- Only reduction of **motor torque**
- Can **cancel static torque**
Application to prosthetics

AMP-foot 4

CYBERLEGs Beta-prosthesis
Application to prosthetics

Inertia has a huge impact!

Verstraten et al., *On the Importance of a Motor Model for the Optimization of SEA-driven Prosthetic Ankles*, Wearable Robotics (WeRob) 2016
Application to prosthetics

Measurements on Cyberlegs prosthesis

Due to motor inertia!
Application to prosthetics

Motor limitations influence spring selection

Optimization, based on

$$C = \int |P_{\text{mech}}| dt$$

Verstraten et al., Optimizing the Power and Energy Consumption of Powered Prosthetic Ankles with Series and Parallel Elasticity, M&MT (under review)
Improving efficiency: Redundance
Dual-motor actuator (DuPG)
Improving efficiency: DuPG

- Designed to replace conventional actuator
- Results:
  - Lower energy consumption
  - 40% weight reduction
  - 56% volume reduction
Mathijssen et al., *Drastic actuator energy requirement reduction by symbiosis of parallel motors, springs and locking mechanisms*, ICRA 2016
Marco Hopper II
Marco Hopper II

- Leg with 2 segments (shank/thigh)
- Hip/foot: linear motion
- Actuation:
  - Motor
  - Planetary gearbox
  - Spindle
  - Bowden cable
  - Pulley (knee)
Virtual Model control

Concept:
• Cancel system dynamics
• Replace with spring-mass dynamics
• Tune stiffness of virtual spring
Video - February 2017
Improvements to setup

• IMU => potentiometer
• Friction compensation
• State machine:
  – Extension
  – Flight
  – Compression
• More complex state transitions
• Improved “zero force mode” in flight
Rigid actuation

- Stable hopping height: 6 cm
- Increased frequency
With series spring
With series spring

First (visual) observations:
• Better stability
• Smaller impact forces
• Lower $\Delta W$
• Lower hopping frequency
• Stable hopping height: 3-4 cm
Future work

SEA-driven hopper
- Increase hopping height
- Compare electrical energy consumption with rigid actuation

DuPG-driven hopper
- Show feasibility on setup
- Measure energy consumption
Thank you for listening!