Building a Robotic Leg for **High Impact Landing**

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Bipedal Seminar
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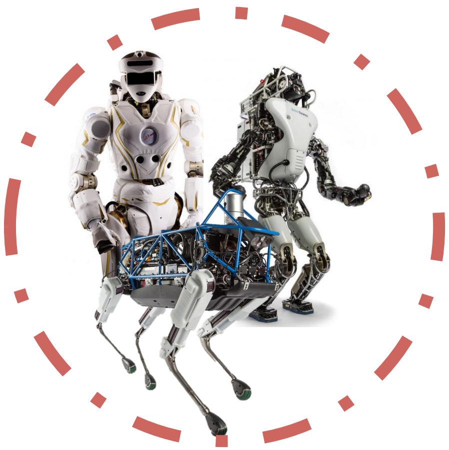
Acknowledgments:
Ben Brown

Content

- Background
- Problem Statement
- Proposed Hardware design
- Simulation & Test
- Results
- Conclusion

Background

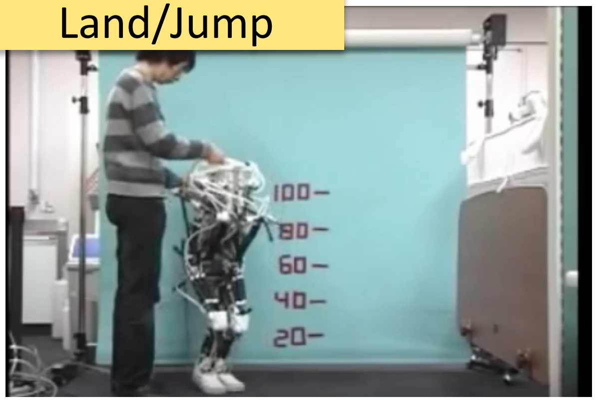
Background cont.



Walk & Run

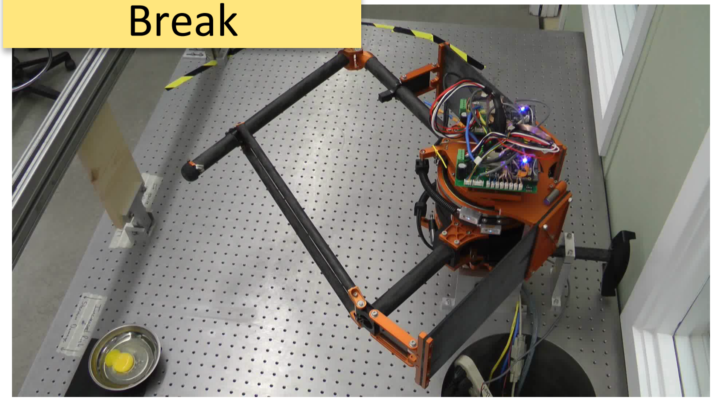
[]

Land/Jump



[2010 Niiyama, R.]

Break



[https://www.youtube.com/watch?v=PmMeY1F9V3I]

Why study jumping?

Search & Rescue

Exploration (space)

Service

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Problem Statement

Aim:

- Design, build and test a new bipedal robot capable of safely landing drop jumps of at least 3m.

Approach:

- Two prong attack
  - Mechanical Hardware **TODAY**
  - Controls

Problem Fundamentals

- Impulse-momentum theorem

$$\overbrace{F \cdot t}^{\text{Post impact Impulse}} = \underbrace{M\Delta\vec{v}}_{\Delta\text{Momentum = constant}}$$

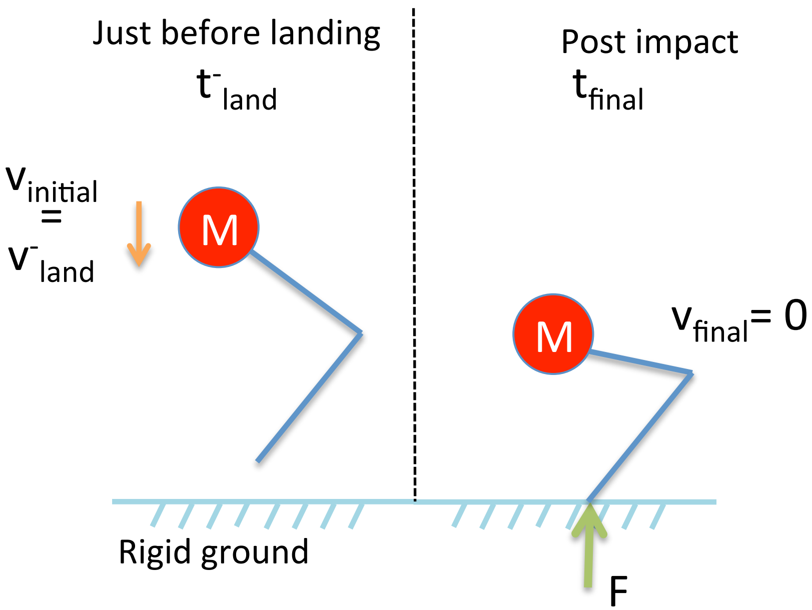
$$\therefore \min F \implies \max t$$

$$\max t \implies \min \dot{v}$$

- **Problem:**

  How do we minimize deceleration?

  + remove energy ?



Specific Challenges

Motor & Transmission

- High torque vs. low gear ratio
- Power consumption
- Gear train is fragile (usually 1st thing to break)

Force Sensing

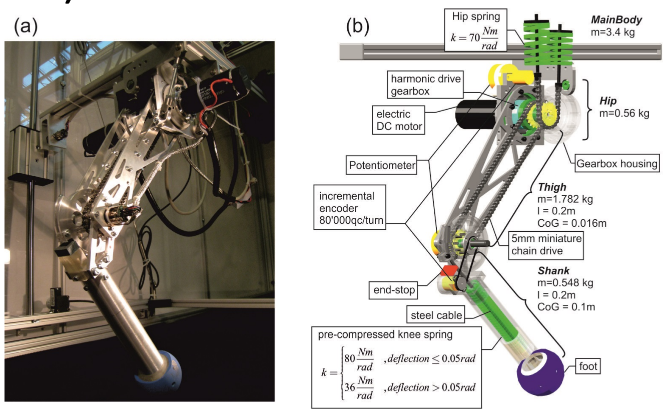
- Accurate sensing on foot
- Strain gauges get saturated
- Can't carry a force plate everywhere

Other

- ~0.5 sec action time
- Adaption to different heights/forces
- Form factor restrictions

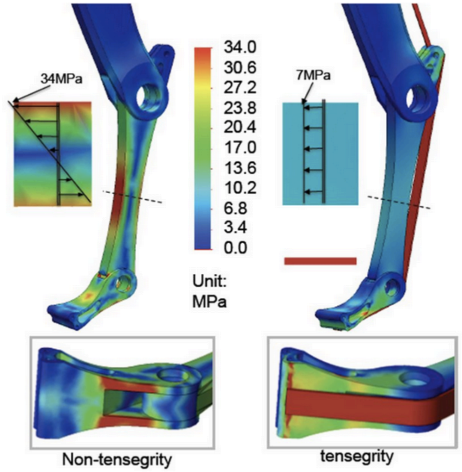
Some current solutions

SEAs (compliant joints)



[Hutter, M., et al. 2011]

Emulating Tendons



[Ananthanarayanan, A., et al. 2012]

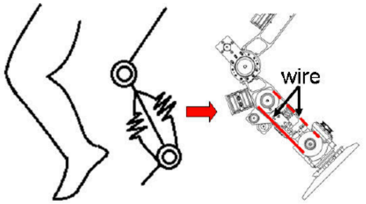


Fig. 5. Comparison with human leg ,simple figure, and large output leg

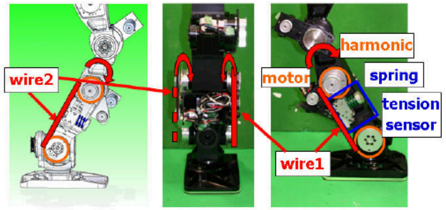
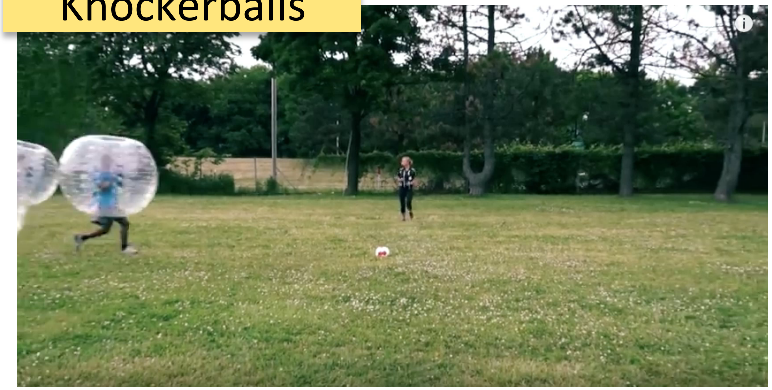


Fig. 6. Mechanism of the tendon-driven ankle joint in developed leg

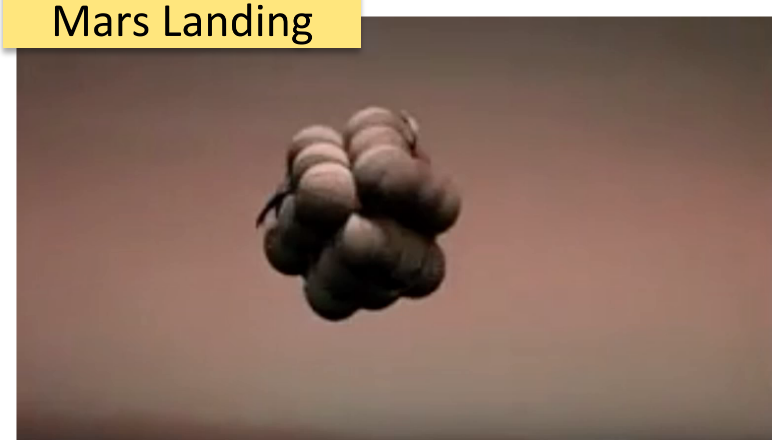
[Ito, Y., et al. 2012]

Potential solution: Airbags

“Knockerballs”



Mars Landing



Pros:

- Simple and effective
- Can be adapted to most systems

Cons:

- Reduces mobility (i.e. arms)
- Uncontrollable
- One time use
- Bulky

More CONs than PROs!

Sorry Chris !

Potential Solution: Active suspension

MR Dampers

Magneto-rheological fluid:

- oil + iron particles
- Control viscosity of fluid by a magnetic field

Model:

$$F_d(x, \dot{x}, i) = (\alpha_0 + \alpha_1 \sqrt{i}) \tanh[\beta_0 \dot{x} + \gamma_0 \operatorname{sgn}(x)] + \delta_0 x + \eta_0 \dot{x} + \kappa_0$$

Pros:

- High shock absorber
- Actively tune for different scenarios
- Proven to work in large system
- Relative small form factor
- Simple to use

Cons:

- Heavy (~5kg)
- very non-linear dynamics
- ~15-20ms reaction time

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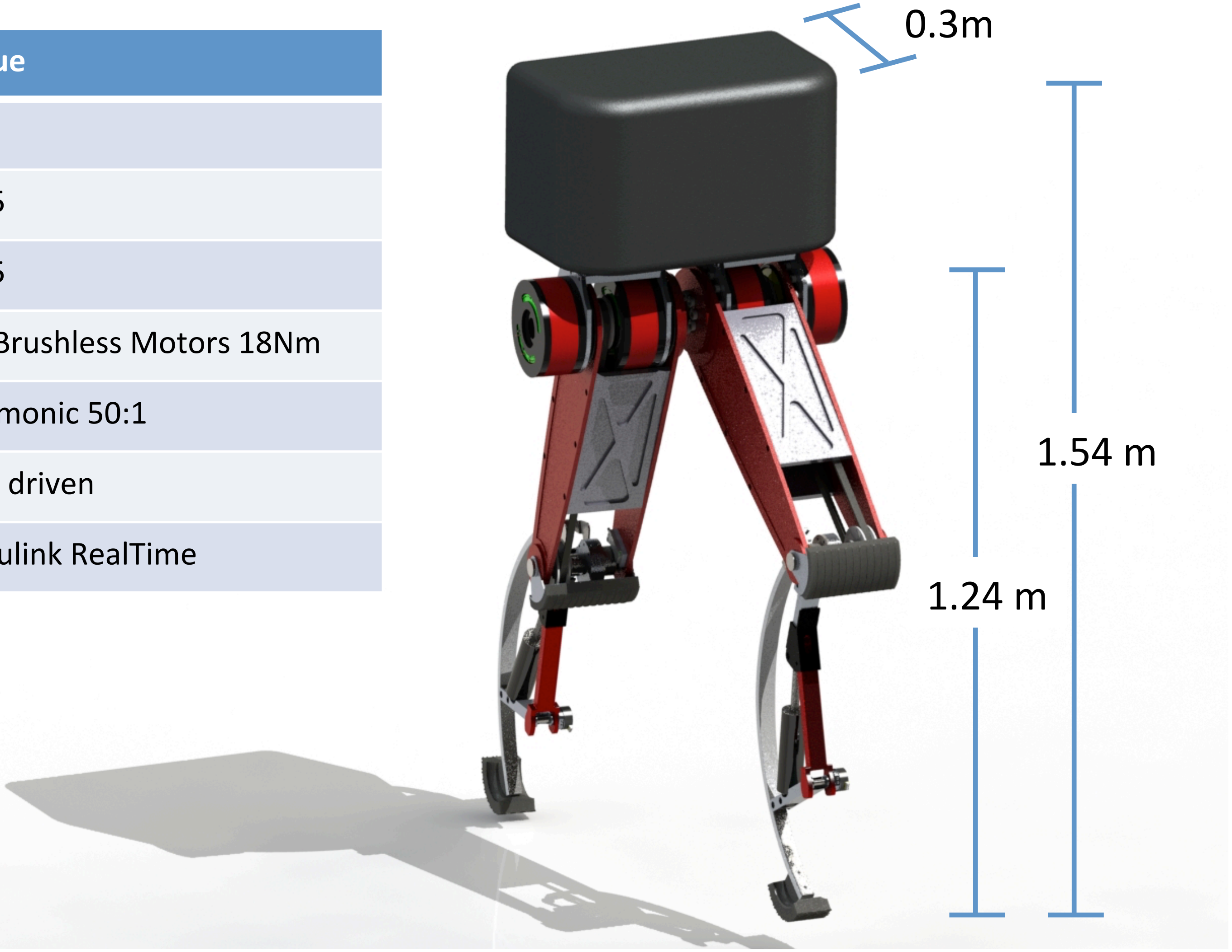
Design overview

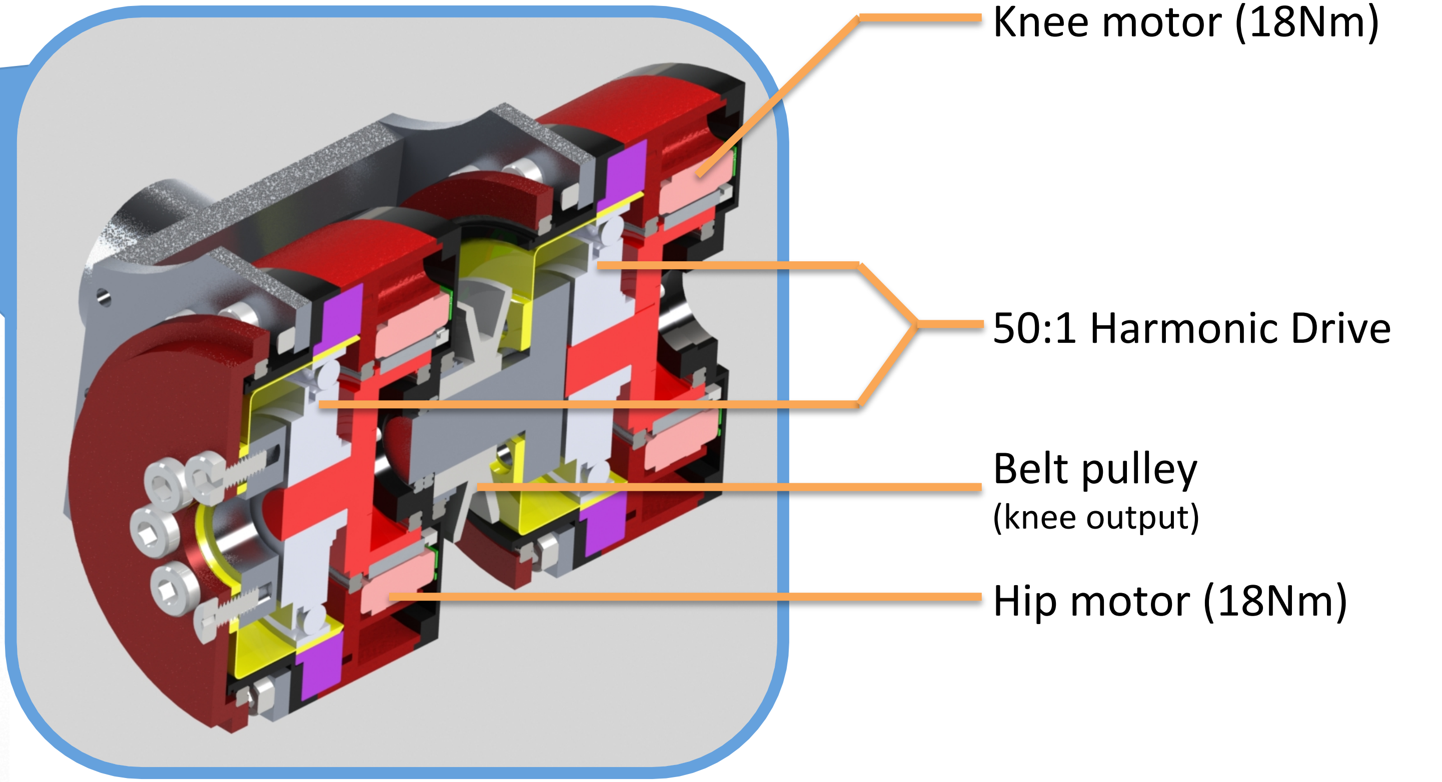
Desired Functionality	Design choice
Impact force attenuation	Variable damping
Force sensing & increasing impact time	Passive compliance
High agility	Low inertia legs
Lightweight and Load bearing	AL 7075-T6
High torque actuation	18Nm motors + 50:1 Harmonic Drive

CAD Model

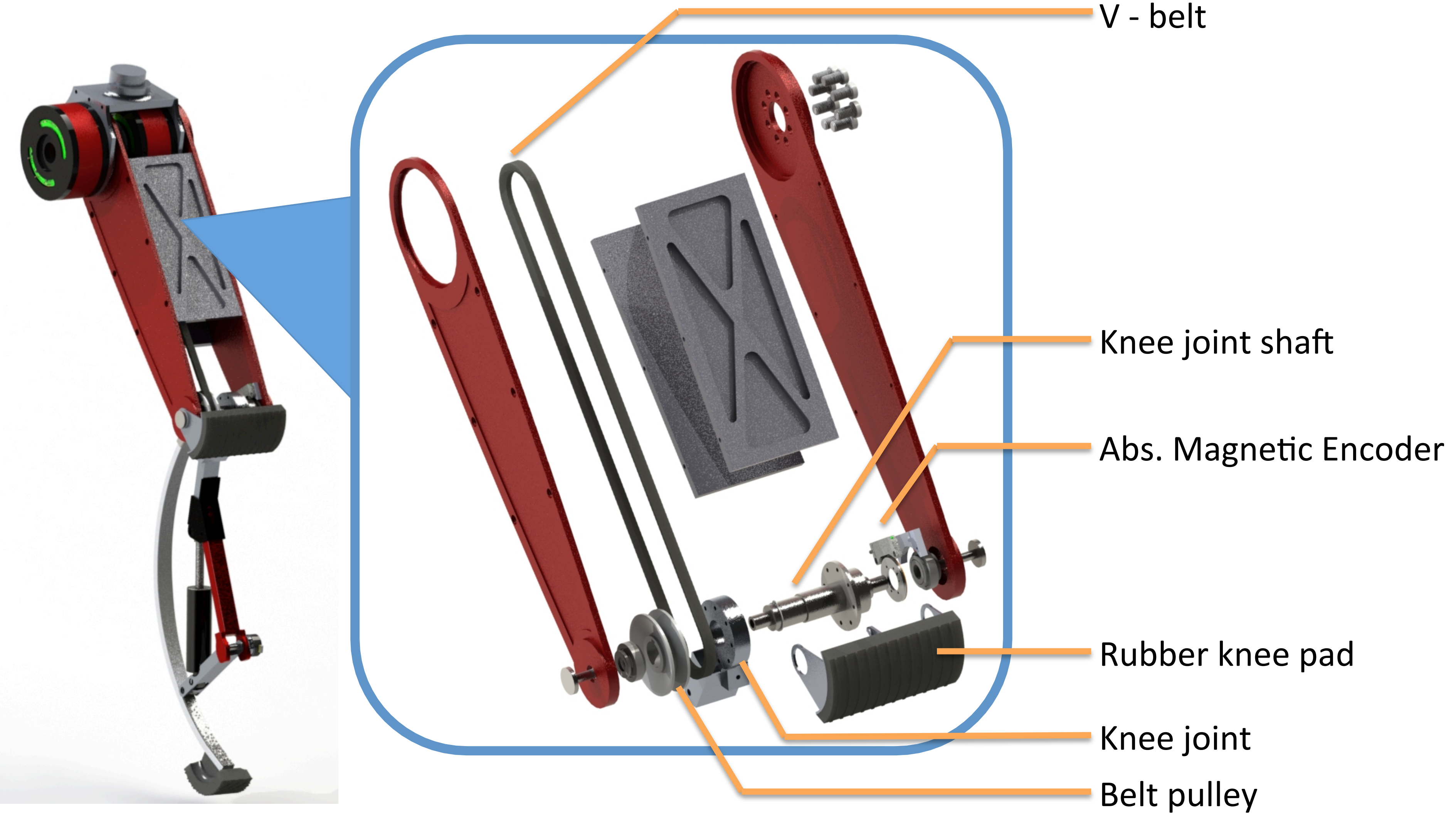
Spec	Value
Mass [kg]	40
Thigh length [m]	0.55
Shin length [m]	0.65
Actuation	DC Brushless Motors 18Nm
Transmission	Harmonic 50:1
Knee drive	Belt driven
OS	Simulink RealTime



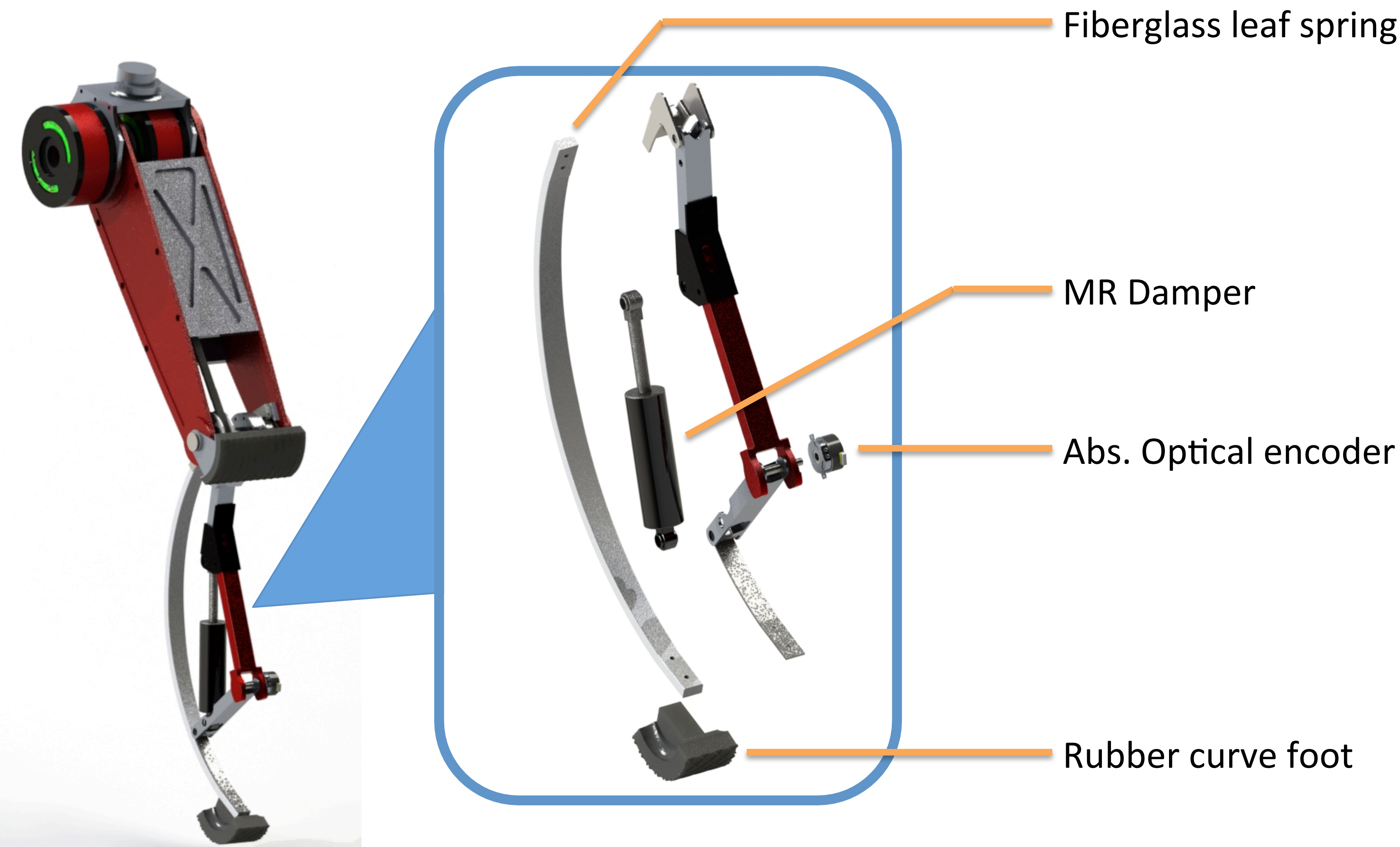
Motors & Transmission



Thigh & knee


V - belt
Knee joint shaft
Abs. Magnetic Encoder
Rubber knee pad
Knee joint
Belt pulley

Shin & Foot


Fiberglass leaf spring
MR Damper
Abs. Optical encoder
Rubber curve foot

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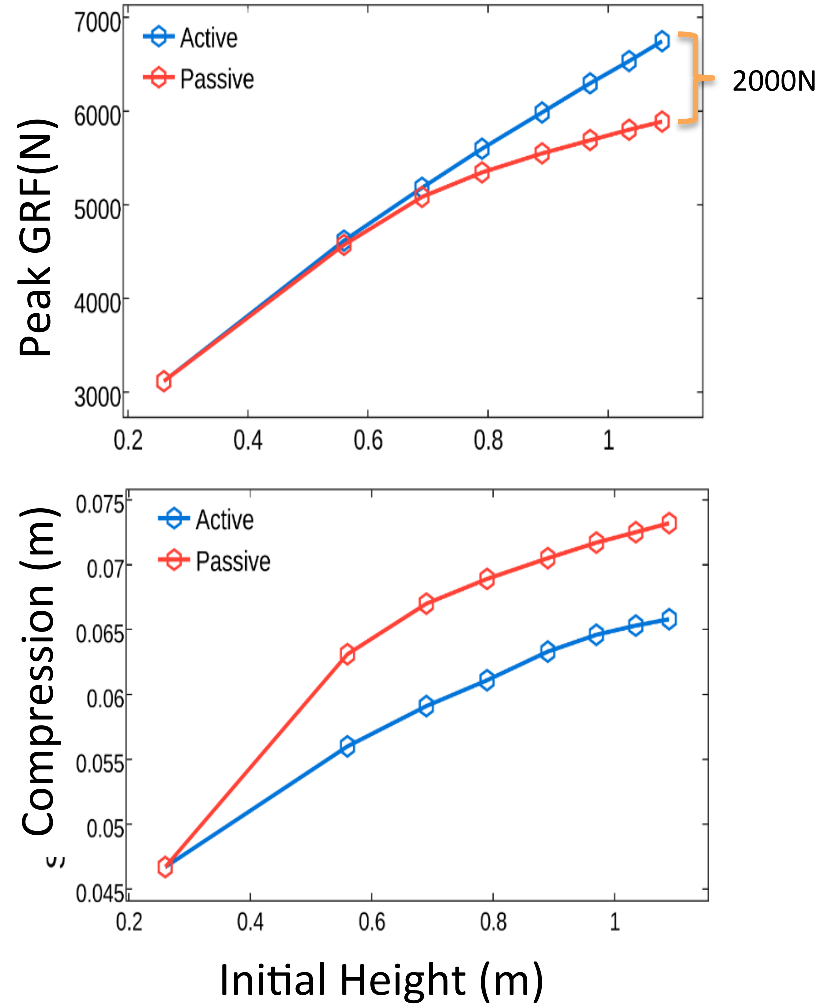
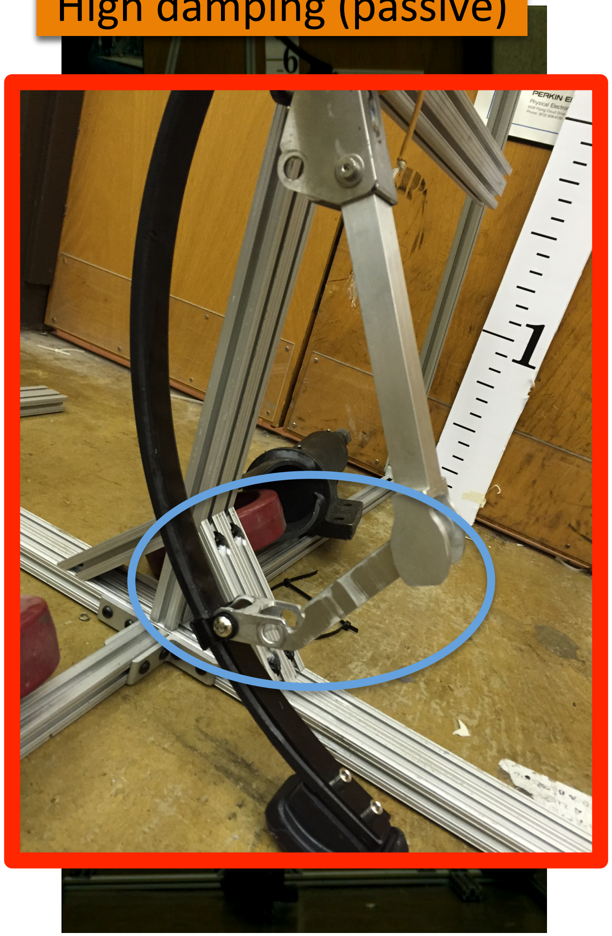
Shin drop test (simulation)



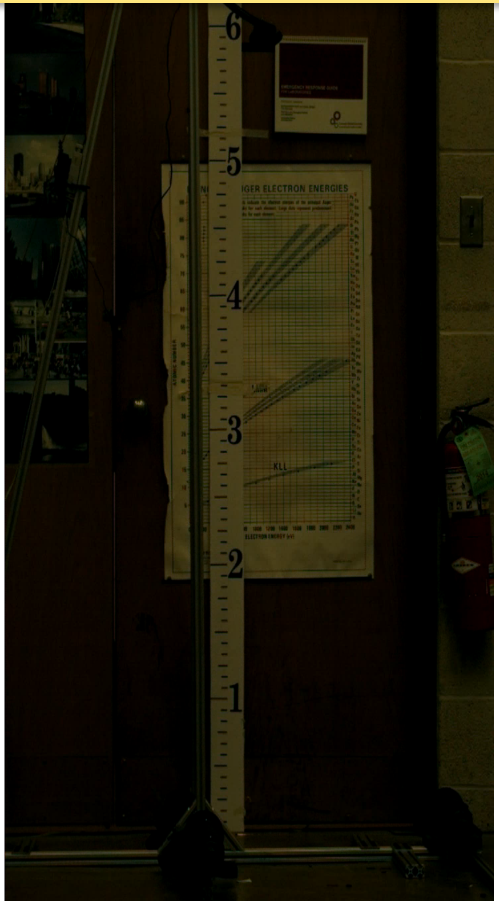
Shin drop test (real)

No damper

High damping (passive)



Damper on (max setting)



Remarks

- Leg was designed for large initial energy
  - (mass and height)
- Increased energy (mass + height) → Broke leg
  - (mechanical rather than conceptual error)
  - Part has been redesigned

Increasing breaking distance

- Breaking distance:
  - Distance it takes to come to a complete stop after impact
- Directly correlated to increasing time in:

$$F \cdot t = M \Delta \vec{v}$$

- Biomechanics → Adding Knee flexion (cushioning reflexion)
- Knee flexion is highly dependent in pre-impact knee:
  - angular position
  - stiffness

Optimization:

- Find optimum gain for impedance control:

$Kp_{hip}(t)$ Stiffness of hip joint
$Kd_{hip}(t)$ Damping of hip joint
$Kp_{knee}(t)$ Stiffness of knee joint
$Kd_{knee}(t)$ Damping of knee joint
$B_{shin}(t)$ Damping of shin

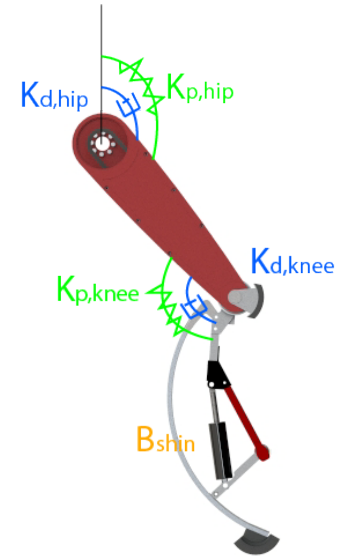


Fig: model used, built in SimMechanics

- That minimizes:

$$C = \underbrace{I^2}_{\text{Impulse force}} + \int_{t_0}^{t_f} \underbrace{u^T Q u}_{\text{Input torques}} + \underbrace{\frac{1}{\alpha_k^T W \alpha_k}}_{\text{Knee flexion}} + \underbrace{y_f^T P y_f}_{\text{Foot vertical pos. rel. to ground}} \quad dt$$

Optimization

- Subject to our hardware constraints:

$$\left.\begin{aligned}\alpha_{\mathrm{h,min}} &\leq \alpha_{\mathrm{hip}} \leq \alpha_{\mathrm{h,max}} \\ \alpha_{\mathrm{k,min}} &\leq \alpha_{\mathrm{knee}} \leq \alpha_{\mathrm{k,max}}\end{aligned}\right\} \text{Joint angle limits}$$

$$\left.\begin{aligned}\tau_{\mathrm{h,min}} &\leq \tau_{\mathrm{hip}} \leq \tau_{\mathrm{h,max}} \\ \tau_{\mathrm{k,min}} &\leq \tau_{\mathrm{knee}} \leq \tau_{\mathrm{k,max}}\end{aligned}\right\} \text{Joint torques limits}$$

$$\left.F_{\mathrm{b,max}} \leq F_{\mathrm{damper}} \leq F_{\mathrm{b,max}}\right\} \text{Damper force limits}$$

- And physical parameters from Solidworks:
  - Mass, Inertia, Size

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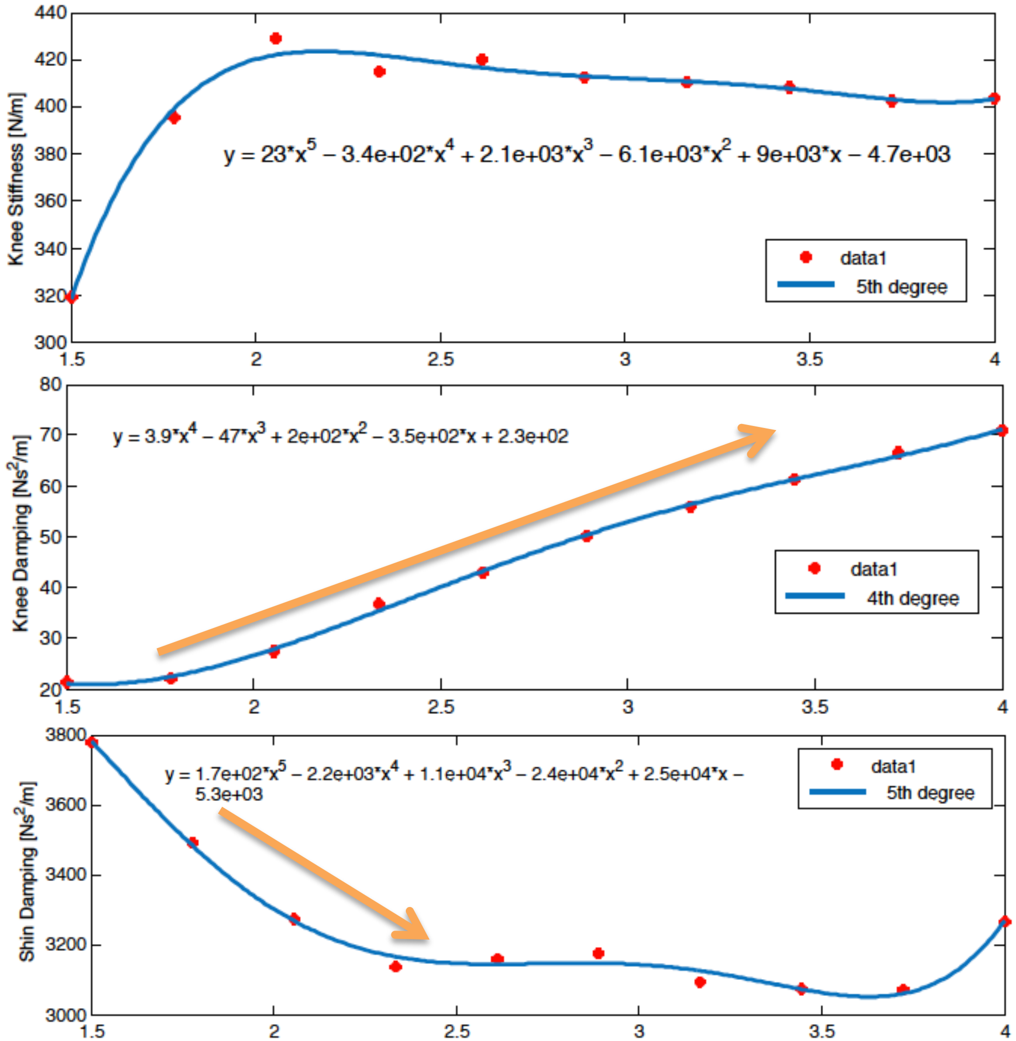
Results

Knee Stiffness

Knee Damping

Shin Damping



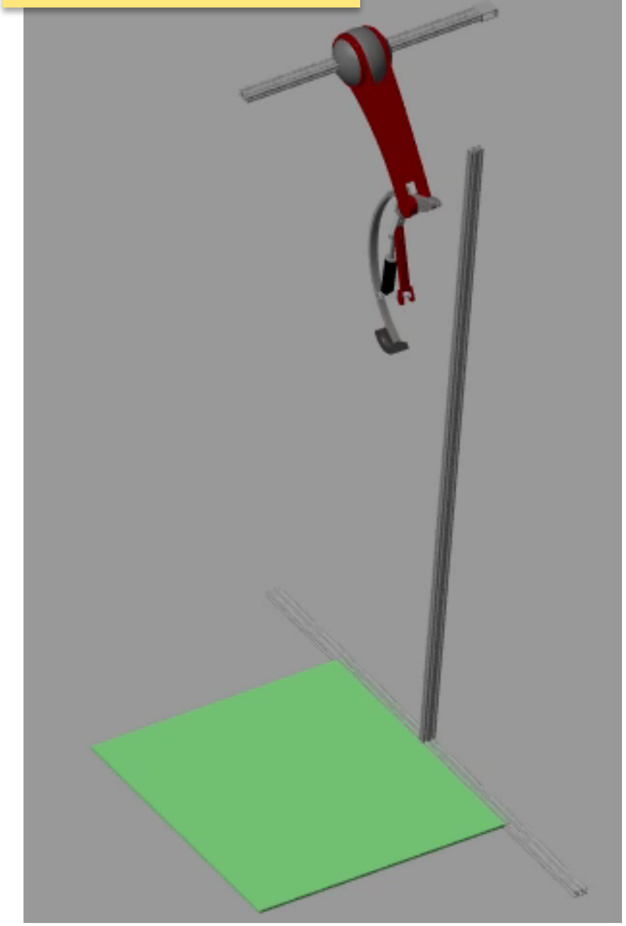
Initial Drop Height [m]

Expected trend:
↑height → damping ↑

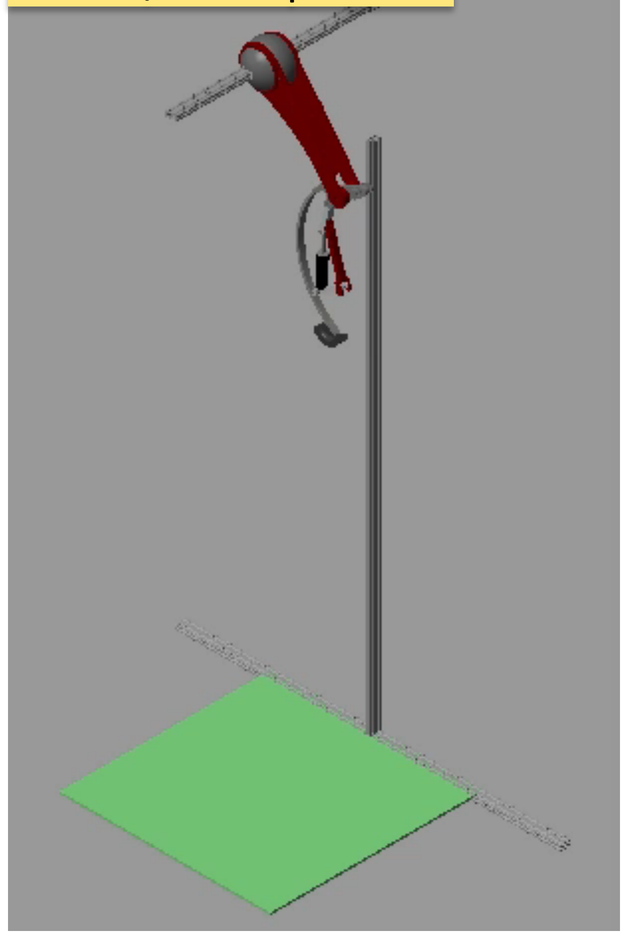
Unexpected trend:
↑height → damping ↓

Results

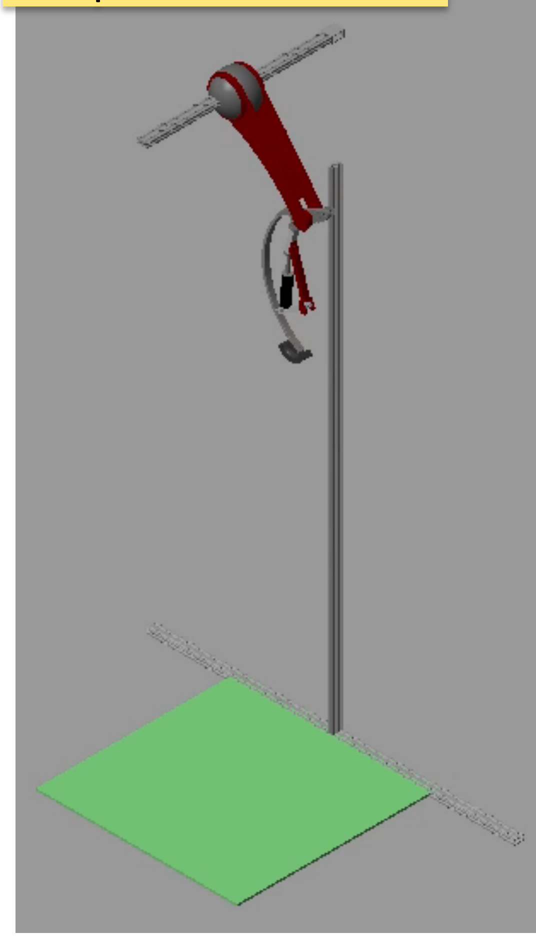
No control



Impedance control
w/o damper



Optimal
Impedance control



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Future work & Open questions

Future work:

- Test on real hardware
- Roll to convert vertical to horizontal momentum

Open Questions:

- How can we more accurately measure GRF?
- What can we do with other measurements (e.g. CoM acceleration)?
- Should the thigh also be compliant?

Q & A

Thank you

Full leg Simulation & Optimization

Use simplified model to find:

$Kp_{hip}(t)$ Stiffness of hip joint
$Kd_{hip}(t)$ Damping of hip joint
$Kp_{knee}(t)$ Stiffness of knee joint
$Kd_{knee}(t)$ Damping of knee joint
$B_{shin}(t)$ Damping of shin

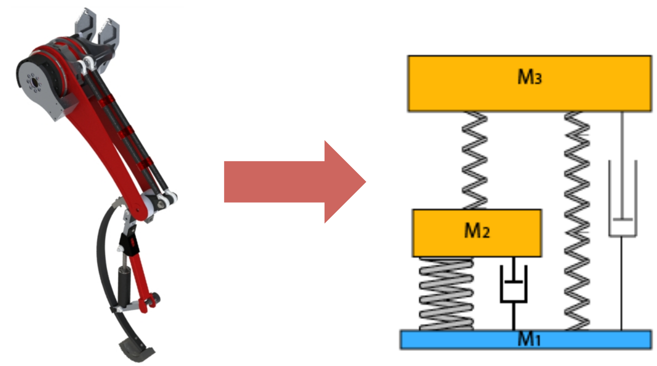


Figure 1: Simplified 3DoF MSD model of robotic leg

2 phase controller

1. "Brace for landing"
    - Leg placement
    - Set stiffness and damping of joint
2. "Energy regulation & stabilizing"
    - Maintain leg placement
    - Use hip torque to slowly decompress the spring

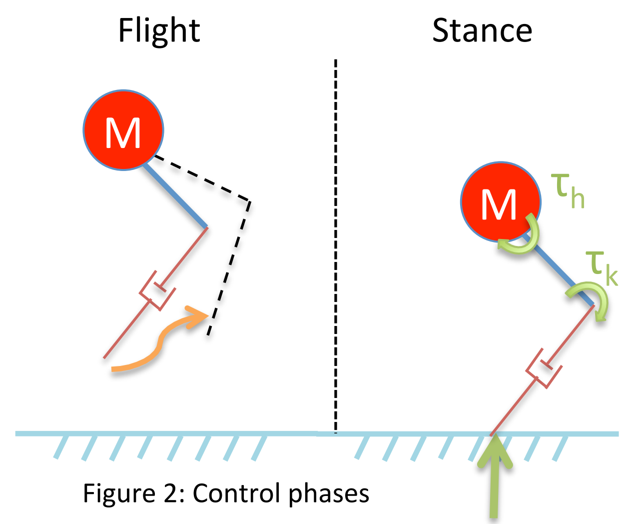
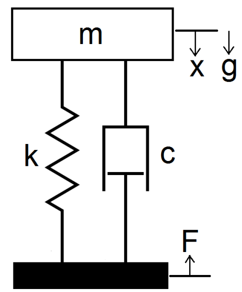
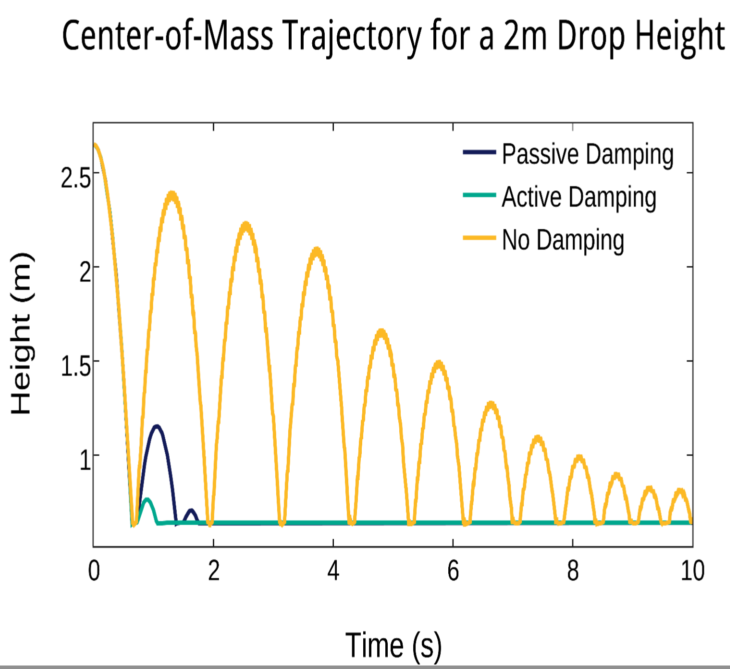


Figure 2: Control phases

Variable damping

- Passive damping only critically damps a small range of jump heights
- Allows for system tuning/ adaptation on the fly
- Shown to improve car suspensions





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High agility	Low inertia legs
Lightweight and Load bearing	AL 7075-T6
High torque actuation	18Nm motors + 50:1 Harmonic Drive
High resolution joint sensing	19Bit Magnetic Absolute Encoder
High frequency communication	EtherCAT
User-friendly target system	Speedgoat + Simulink - RealTime