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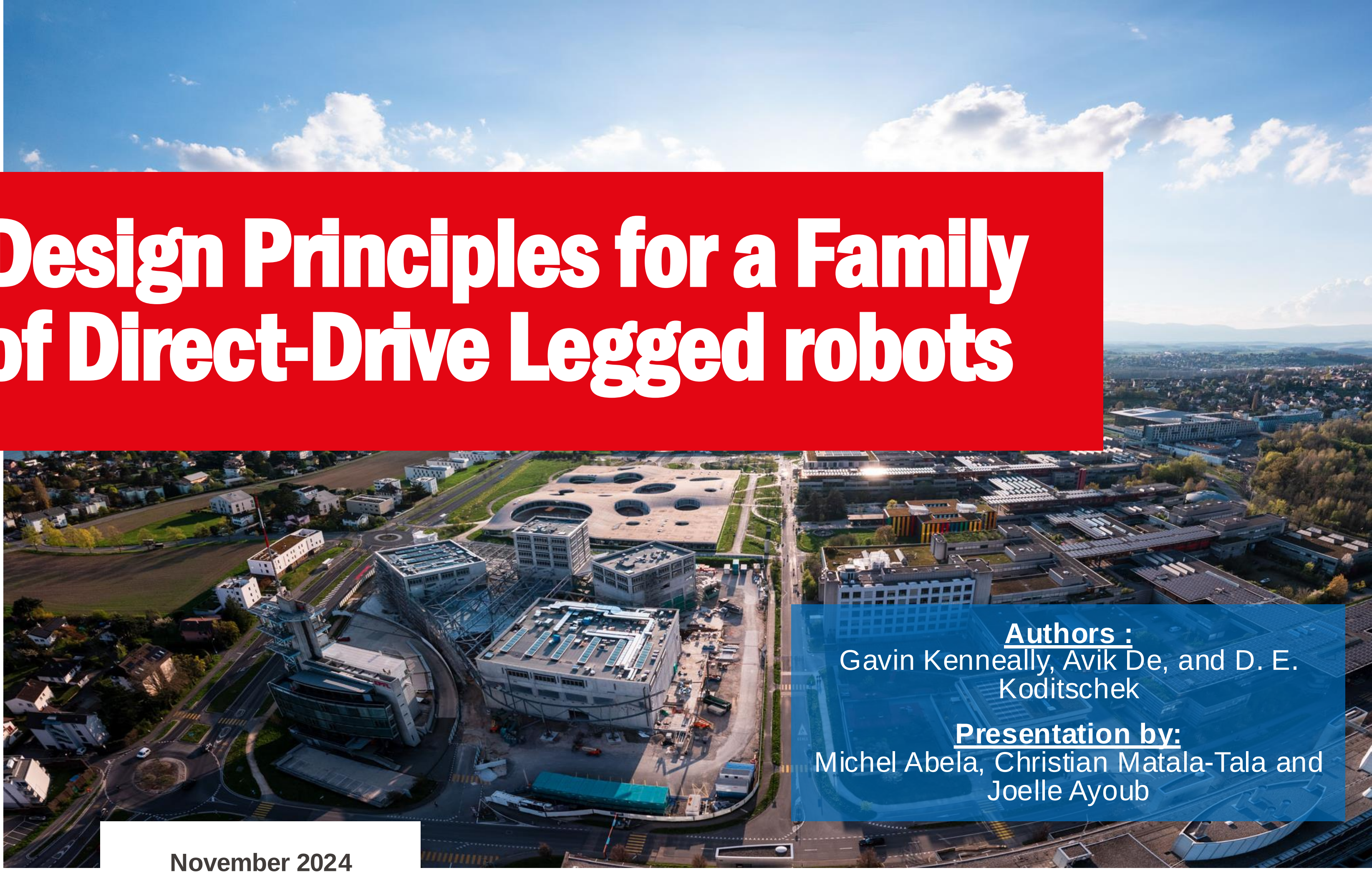
# Design Principles for a Family of Direct-Drive Legged robots

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# Video Introduction

## *Minitaur robot*


https://www.youtube.com/watch?v=kQ_sIcIAP18

## *Penn Jerboa robot*


https://www.youtube.com/watch?v=wvYthkpRFfk

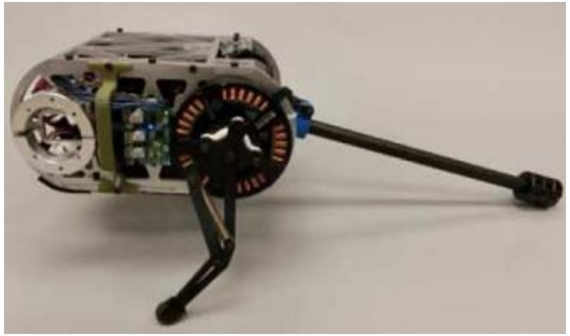
# Direct Drive definition

**Direct-Drive (DD) :** Actuation where motor torque is directly applied to the load, eliminating gears, belts, or chains.

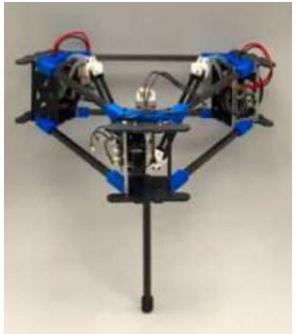
source: AI generated

***Types of robots that use DD:***

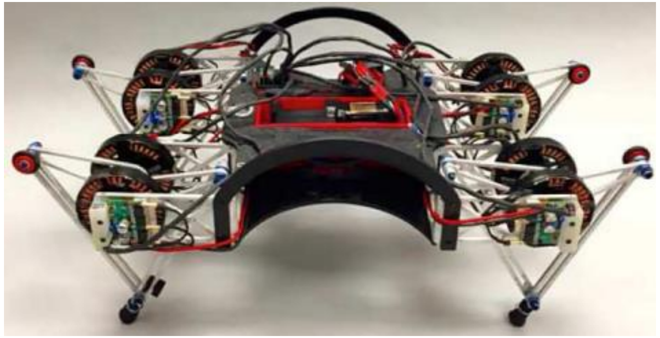
**Tailed Biped:**
*Penn Jerboa*



**Monoped:**
*Delta Hopper*



**Quadruped:**
*Minitaur*



source: this paper "Design principles for a family of direct drive legged robots"

# Why use DD for legged locomotion ?

## Transparency:

**Direct motor dynamics** → Quickly influenced by external forces

**No gearbox** → Eliminates backlash and viscous friction

## Mechanical Performance:

**Robustness & Efficiency** → No gears to protect from impulses & no mechanical loss from gear reduction

**Dynamic Isolation** → Coupled to legs via motor's air gap and bearings

**Control** → Lagrangian dynamics enabled by reduced complexity

## High-bandwidth Signal Flow:

**Better Sensing & Actuation** → Reduces low-pass filtering effects.

**Tunable Compliance** → Achieved at kHz timescales for precise control.

## Specific Power:

**Peak Performance** → Higher than geared counterparts (no power loss from gear reduction)

# DD Setbacks

**No Gearbox** → Can’t amplify the output torque and decrease the output speed

**High Torque/Low Speed** → Significant Joule heating

**Peak Performance** → Actuators operate far from peak power and efficiency

**Thermal Inefficiency** → Increased energy loss due to heating

# Metrics needed to classify DD motors



**Peak Specific Torque**

*(instantaneous performance)*

*limited by flux saturation of the motor's core*

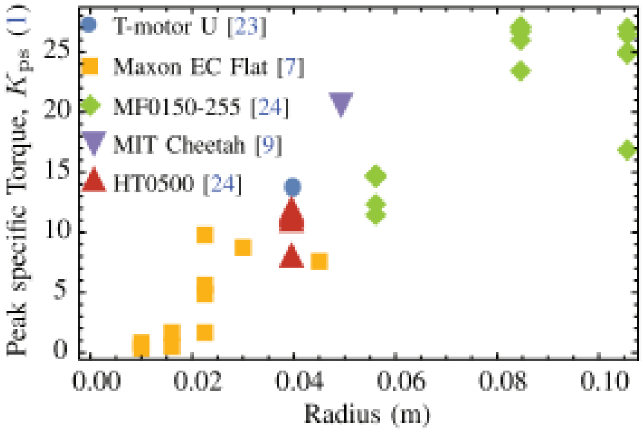
**Thermal Specific Torque**

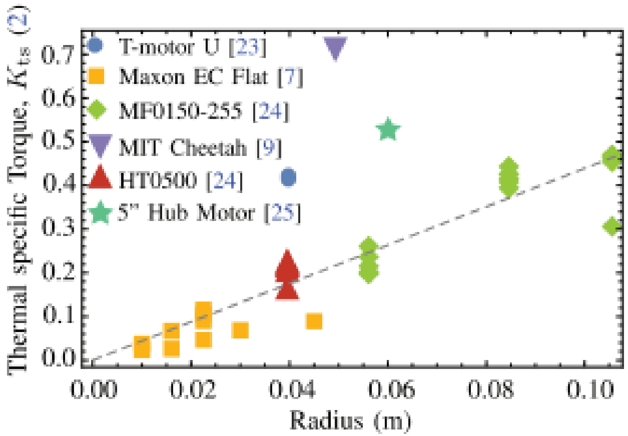
*(steady performance)*

*limited by the winding enamel's maximum temperature at stall*

$$K_{\text{ps}} := \frac{K_t i_p}{m} \qquad \left(\text{in units of } \frac{\text{Nm}}{\text{kg}}\right)$$

$$K_{\text{ts}} := \frac{K_t}{m}\sqrt{\frac{1}{R_{\text{th}}R}}, \qquad \left(\text{in units of } \frac{\text{Nm}}{\text{kg}\sqrt{^\circ\text{C}}}\right)$$




*Both plots have a quite linear trend between specific torque and gap radius*

# Actuator Recruitment via Leg Design

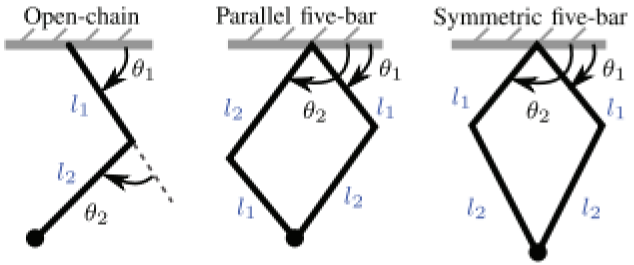
Explored various leg designs with 1 to 3 actuated Degrees of Freedom (DOF)

We define:

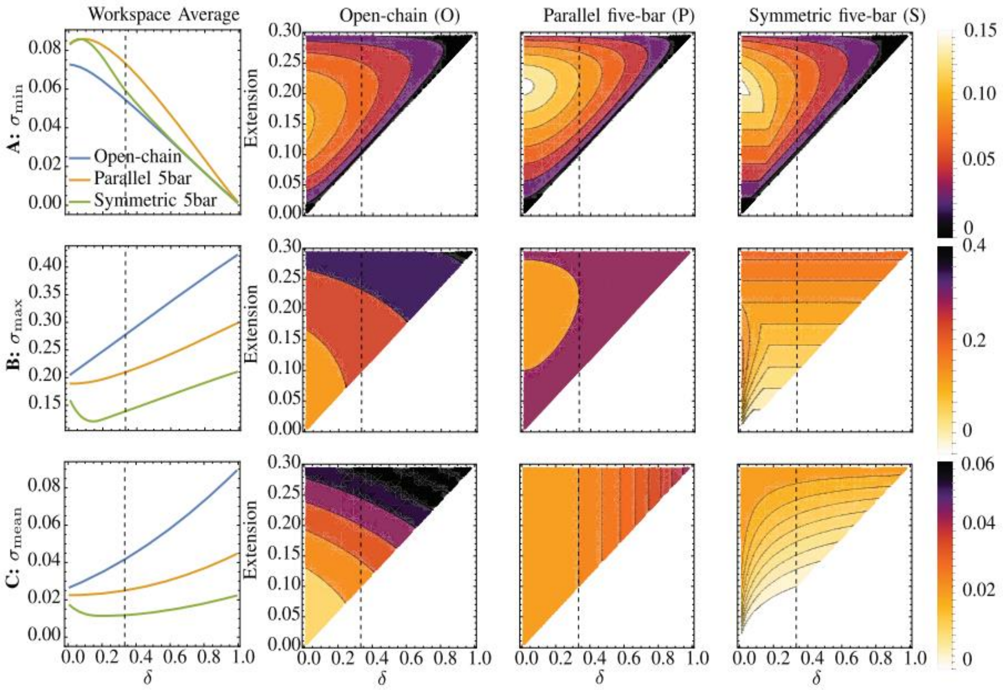
1. Design Space (delta) $$\delta = \frac{r_{\min}}{r_{\max}} = \frac{|l_1 - l_2|}{l_1 + l_2}$$

2. Workspace variable y (radial extension of the leg)

   Different 2-DOF simple kinematics



# Measuring & Plotting results




## Metrics used:

- ***Proprioceptive Sensitivity ($\sigma_{min}$):***

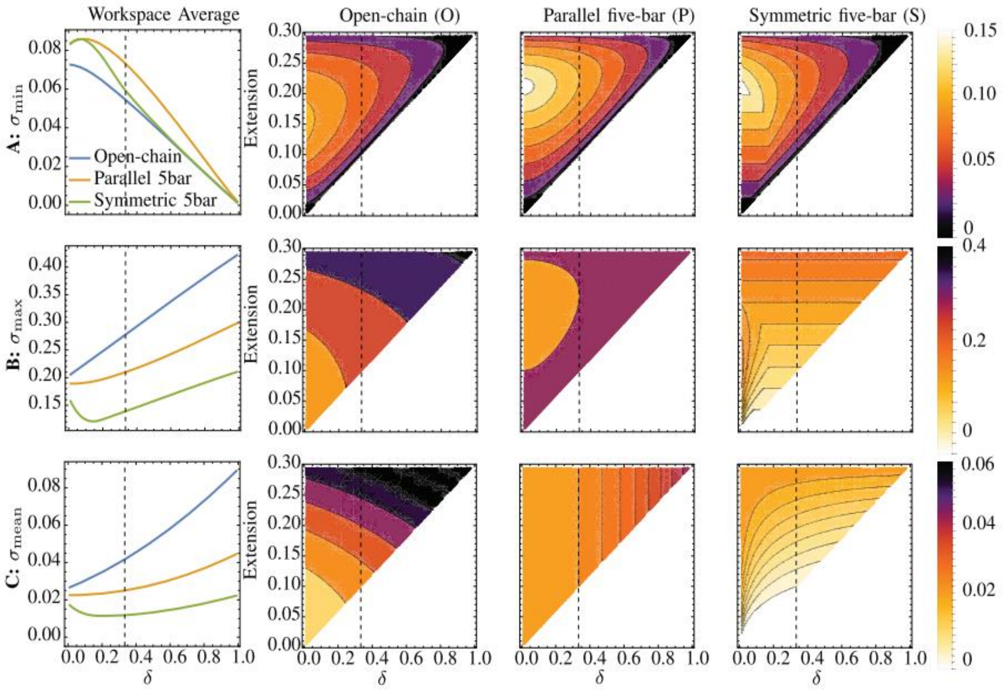
Minimal speed of the toe in any direction for a given motor angular velocity

- ***Force Production ($\sigma_{max}$)***

Degree to which an arbitrary external force can be resisted by the actuators

- ***Thermal Cost of Force ($\sigma_{mean}$):***

# Measuring & Plotting results




## Results:

- ***Higher* values of σmin are favorable:** The two parallel mechanisms have better proprioception through a larger portion of their workspace
- ***Lower* values of σmax are favorable:** The symmetric five-bar does consistently better than the other two mechanisms
- The symmetric five-bar has superior design-averaged performance than the others

# Comparing with conventional gear design



Direct Drive motor:
T-Motor U8

Maxon EC-45

# Transparency



TABLE I
COMPARISON OF SPECIFIC CONVENTIONAL AND DD ACTUATORS

| | EC45-70W, 23:1 | U8 |
|---|---|---|
| Mass (kg) | 0.35 | 0.25 |
| $K_v$ ($\frac{\text{rev}}{V\text{sec}}$) | 0.188 | 1.67 |
| Continuous Torque (Nm) | 2.95 | 0.855 |
| Peak Torque (Nm) | 18.86 | 3.5 |
| Max Continuous Power @15V (W) | 12.18 | 35.63 |
| Reflected Inertia (kg-m$^2$) | 0.0096 | 0.0001 |
| Static Friction (Nm) | 0.218 | 0.056 |
| Kinetic Friction (Nm) | 0.088 | 0.023 |
| Viscous Friction ($\frac{Nm}{rad/s}$) | 0.0071 | 0.00013 |
| Backlash (deg) | 0.8 | 0 |

## Results:

### Advantages of the Direct Drive U8 Motor:

- Reflected inertia 96x higher
- Static friction 3.98x higher
- Kinetic friction 3.83x higher
- Viscous drag. 54.6x higher

### Advantages of the Maxon EC-45 Motor:

- Continuous torque 2.5x higher
- Peak specific torque 5.39x higher

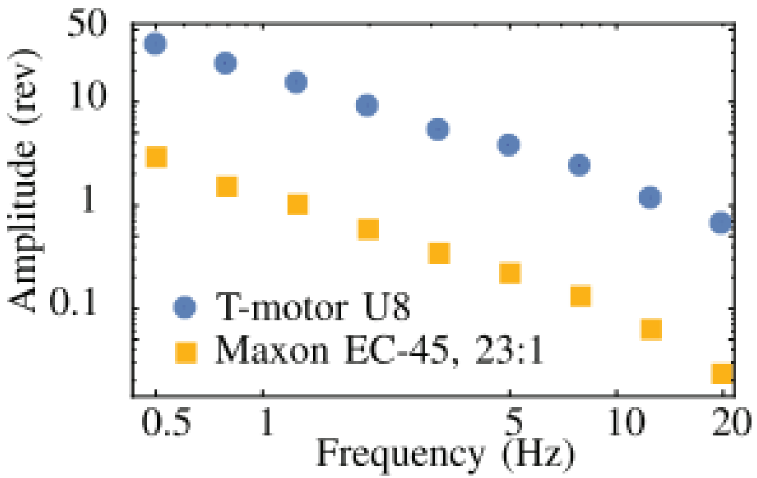
# Actuation Bandwidth



**Experiment:**
Command motors with open-loop sinusoïdal voltage at various frequencies.

**Results:**
U8 performed better with 17.4x more rotations than the EC-45.

**Measurement:**
Output shaft of the motor in revolutions



# Performance Metrics

- Steady velocity:Vss
- Vertical Specific agility: $\alpha_v = h_{\max} g$
- Minimal continuous vertical acceleration: $a_{\mathrm{mcv}} := \frac{\tau_c n_l}{mg} \left( \min_q \Gamma_v(q) \right) - 1$
- Cost of Transport: $CoT := \frac{Vi}{Mgv_{\mathrm{ss}}}$

TABLE II
PHYSICAL PROPERTIES OF THE MACHINES OF INTEREST (II-C)

| Robot | Legs | DOF | $L$ (m) | $M$ (kg) | Mot. (%) | $G$ |
|---|---|---|---|---|---|---|
| Minitaur | 4 | 8 | 0.2 | 5 | 40 | N/A |
| Delta Hopper | 1 | 3 | 0.2 | 2.0 | 38 | N/A |
| Jerboa | 2 | 4 | 0.105 | 2.5 | 40 | N/A |
| MIT Cheetah | 4 | 12 | 0.275 | 33 | 24 | 5.8 |
| XRL | 6 | 6 | 0.2 | 8 | 11 | 23 |
| ATRIAS | 2 | 6 | 0.42 | 60 | 11 | 50 |
| StarlETH | 4 | 12 | 0.2 | 23 | 16 | 100 |
| Cheetah Cub | 4 | 8 | 0.069 | 1 | 16 | 300 |

TABLE III
PERFORMANCE MEASURES OF THE MACHINES OF INTEREST (II-C)

| Robot | $v_{\mathrm{ss}}$ (m/s, LL/s) | $\alpha_v$ (m/s)$^2$ | $a_{\mathrm{mcv}}$ [DD] (g) | CoT |
|---|---|---|---|---|
| Minitaur | $1.45, 7.25$ | 4.70 | 0.69 | 2.3 |
| Delta Hopper | N/A | 3.44 | 0.59 | N/A |
| Jerboa | $1.52, 14.5$ | 1.37 | 0.39 | 2.5 |
| MIT Cheetah | $6, 21.8$ | 4.91 | 1.33 [$-0.60$] | 0.51 |
| XRL | $1.54, 7.7$ | 4.17 | 1.14 [$-0.91$] | 0.9 |
| ATRIAS | $2.53, 6.00$ | N/A | 2.03 [$-0.94$] | 1.46 |
| StarlETH | $0.7, 3.5$ | 3.09 | 0.37 [$-0.99$] | 2.57 |
| Cheetah Cub | $1.42, 20.8$ | 0.20 | 19.38 [$-0.93$] | 9.8 |

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# Conclusion



***PROS***

- Transparency
- Easy control with Lagrangian dynamics
- Little to no mechanical loss thanks to the absence of a gearbox
- Higher peak performance

***CONS***

- Significant Joule heating
- Actuators operate far from peak performance range
- High heat production

# Article Citations

**Source: IEEE Robotics and Automation Letters**

- Google Scholar:
  - → 221 cites in paper
  - → 2 cites in patents
  - → 12701 full text views
- Scopus: 236 cites in paper

**Influence on some other labs:**

- Paper: "Design and Experimental Verification of a Jumping Legged Robot for Martian Lava Tube Exploration", by: Jørgen Anker Olsen, Kostas Alexis
- Paper: “Design and Characterization of 3D Printed, Open-Source Actuators for Legged Locomotion", by: Karthik Urs, Challen Enninful Adu, Elliott J. Rouse, Talia Y. Moore

# Possible exam questions

**Question 1:**
**Why is transparency an important advantage of Direct Drive actuation?**

**Answer:**
Transparency is important because direct motor dynamics allow quick responses to external forces, and the absence of a gearbox eliminates backlash and viscous friction, improving control and interaction with the environment (Slide 3).

**Question 2:**
**2)What are the two types of specific torque used to classify Direct Drive motors and what limits each?**

**Answer:**
Peak Specific Torque: Limited by the flux saturation of the motor's core
Thermal Specific Torque: Limited by the maximum temperature of the winding enamel at stall (Slide 5)

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# Thank you