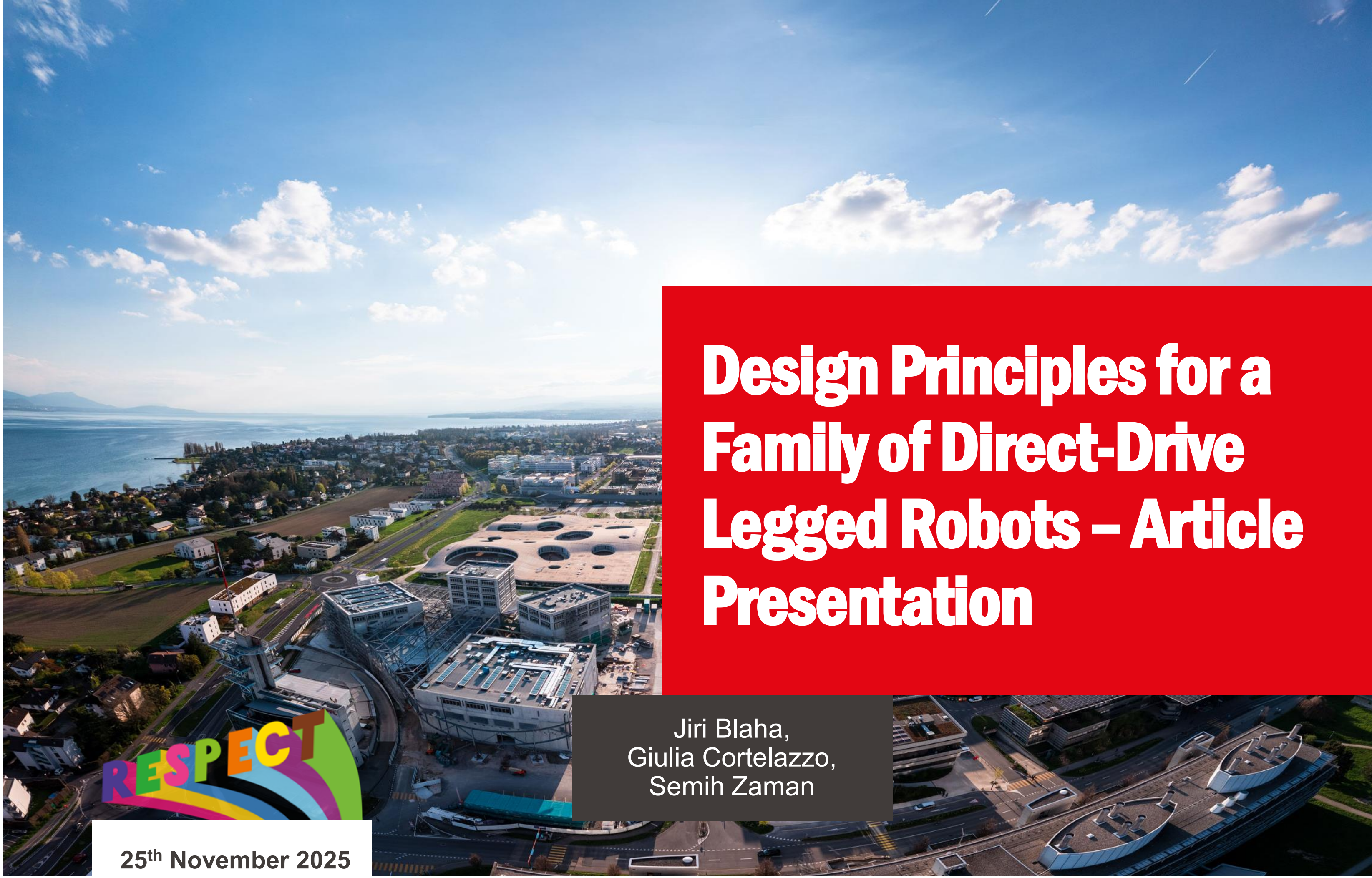
EPFL



# Design Principles for a Family of Direct-Drive Legged Robots – Article Presentation

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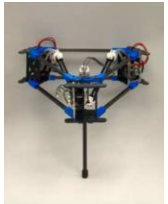
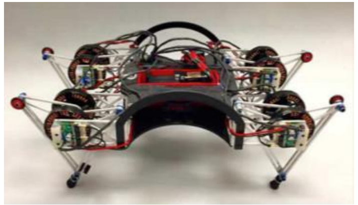
25th November 2025

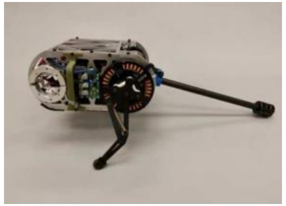
# Direct Drive - Main Idea

- Novel class of direct-drive legged robots
  - Simplify mechanical design and maintain high performance

- Demonstration through three robots:
  - Delta Hopper (monoped, 3 DOF)
  - Minitaur (quadruped, 2 DOF/leg)
  - Jerboa (biped with tail, 1 DOF/leg)







- DD design enables transparency, robustness, and high bandwidth, offering new insights into energetic, proprioceptive, and mechanical behavior

# In Perspective

# Direct Drive - Motivation

✅ Advantages:

- Transparency → no gear friction or backlash
- Mechanical performance → more robust and efficient
- High bandwidth → faster sensorimotor response
- High specific power → lightweight

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❌ Disadvantages:

- Must operate in high torque → heating limits performance and speed
- Complex thermal management
- Energetically inefficient near stall
- Scaling limited by available motors

# Design Methodology

With no gearbox, we lose torque amplification → force scarcity

**Q: How do we mitigate that?**

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**Q: How do we mitigate that?**

- Choice of Motors
  - Pick motors with high sustainable torque → high **peak torque** and **thermal torque density** (need high torque at low speed, e.g., idle stance)
- Leg Geometry
  - Smart leg geometry can mechanically amplify torque → **symmetric 5-bar**
- Mass distribution
  - Dedicate more mass budget to actuators → approx. **40%** for motor (needed for torque/kilogram maximization)
- Leg Workspace
  - Knees above hips → **more leverage** throughout the stride
- Number of DOF
  - Avoid excessive amounts of DOFs → **limits framing costs**

# Empirical Performance



Important outliers mentioned in the article

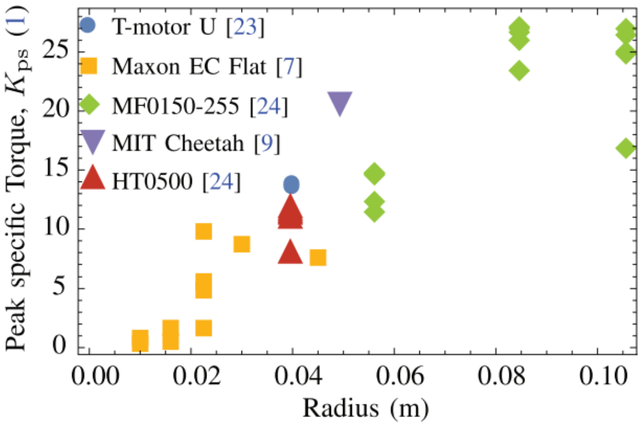


Fig. 2. Peak specific torque (limited by flux saturation; affects instantaneous performance) against gap radius for a selection of legged robot actuators.

(Units: Nm/kg)

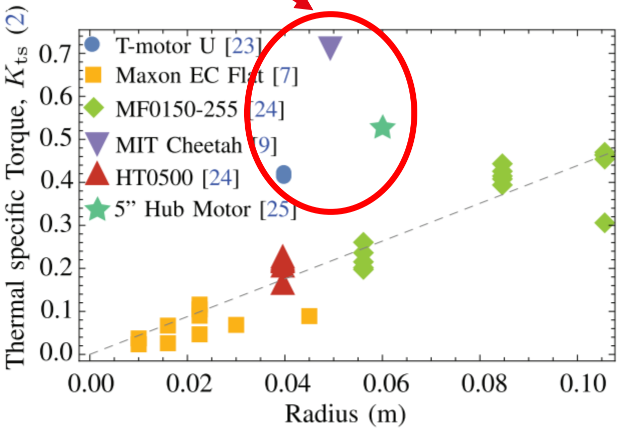


Fig. 3. Thermal specific torque (limited by winding temperature; affects steady-state performance) against gap radius for a selection of legged robot actuators. The dashed line indicates the mean of the "inliers" detailed in Section. II-A.

(Units: Nm/kg/sqrt(°C))

# Locomotive Consequences

- Lower Touchdown Losses
  - Direct-drive + low inertia → **5× less collision energy loss**, improving running stability
- High Proprioception (Feeling the Ground)
  - No gears = no friction/backlash → motors **sense contact instantly**, enabling fast gait transitions
- High Actuation Bandwidth
  - DD motors respond at **kHz-level** → rapid torque changes for agile behaviors (bounding, pronking)
- Robust to Hard Impacts
  - No gearboxes = nothing to break → handles **rough landings** & **unpredictable terrain**

# Conventional vs DD Actuators



TABLE I
COMPARISON OF SPECIFIC CONVENTIONAL AND DD ACTUATORS

| | EC45-70W, 23:1 | U8 |
|---|---|---|
| Mass (kg) | 0.35 | 0.25 |
| $K_v$ ($\frac{rev}{V\sec}$) | 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 |

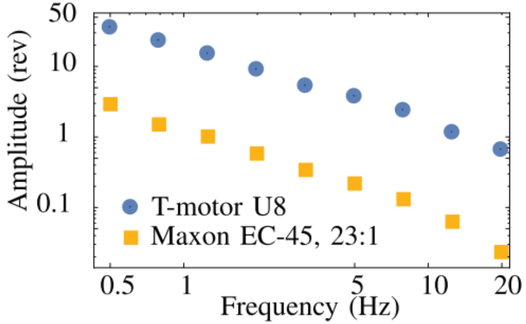


Fig. 6. Bode plot of amplitude response (in revolutions) to sinusoidal voltage input at various frequencies.

- DD actuators have almost no friction, backlash, or reflected inertia → much higher responsiveness.
- DD motors keep large motion amplitudes at higher frequencies, unlike geared actuators.

# Performance Comparison



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 | $v_{ss}$ (m/s, LL/s) | $\alpha_v$ (m/s)$^2$ | $a_{mcv}$ [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 |

- DD robots use fewer DOF and higher motor mass %, while geared robots use many DOF and gear reductions.
- $a_{mcv}$ provides a necessary condition: whether a legged robot will be suitable for DD operations: Actuators, Linkages, Leg configuration, Length scale

$$a_{mcv} := \frac{\tau_c n_l}{mg}\left(\min_q \Gamma_v(q)\right) - 1$$

- DD robots show healthy $a_{mcv}$ values and good speed, while geared robots trade $a_{mcv}$ for higher top speeds.

# Influence, Citations

Scopus

Back

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

IEEE Robotics and Automation Letters • Article • 2016 •
DOI: 10.1109/LRA.2016.2528294

Kenneally, Gavin [a]; De, Avik [b]; Koditschek D.E. [b]
[a] Department of Mechanical Engineering and Applied Mechanics, University of Pennsylvania, Philadelphia, 19104-6315, PA, United States

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Citations

8.47
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Gavin Kenneally
Graduate Student University of Pennsylvania
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| TITLE | CITED BY | YEAR |
| --- | --- | --- |
| Design principles for a family of direct-drive legged robots<br>G Kenneally, A De, DE Koditschek<br>IEEE Robotics and Automation Letters 1 (2), 900-907 | 437 | 2016 |

Most cited article of the first author Gavin Kenneally

https://www.scopus.com/pages/publications/85058585196?origin=resultslist
https://scholar.google.com/citations?view_op=list_works&hl=en&hl=en&user=1L9nPNEAAAAJ

# In Perspective

- Future work mentioned:
  - optimize **energy efficiency**
  - **exploit proprioception** - feel via motor currents or torque rather than external sensors
- Ghost Robotics

https://medium.com/penn-engineering/introducing-ghost-robotics-and-minitaur-d6019d9698ff
https://spectrum.ieee.org/ghost-robotics-minitaur-quadruped

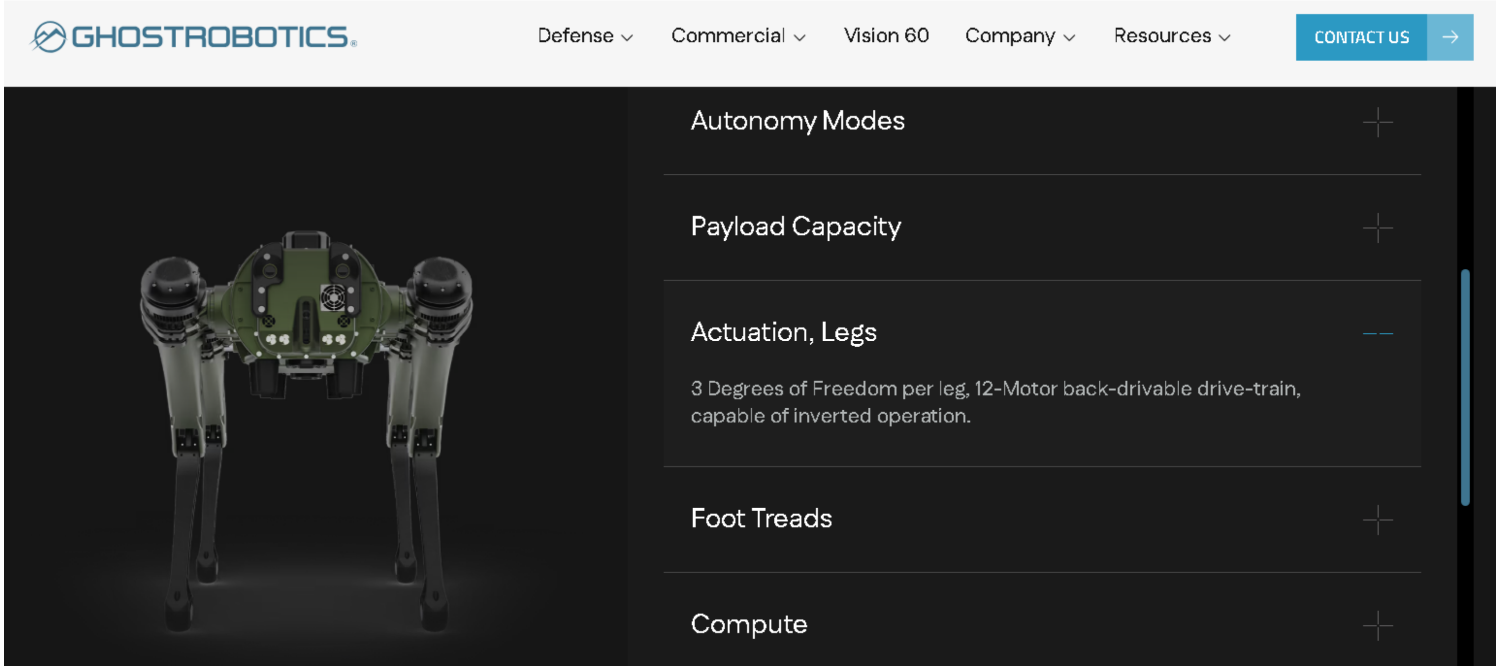
# In Perspective



- Ghost Robotics

# In Perspective

- Ghost Robotics → military




https://www.ghostrobotics.io/vision-60
https://medium.com/@ghostrobotics/introducing-ghost-robotics-and-minitaur-d6019d9698ff
https://spectrum.ieee.org/ghost-robotics-minitaur-quadruped

# Analysis



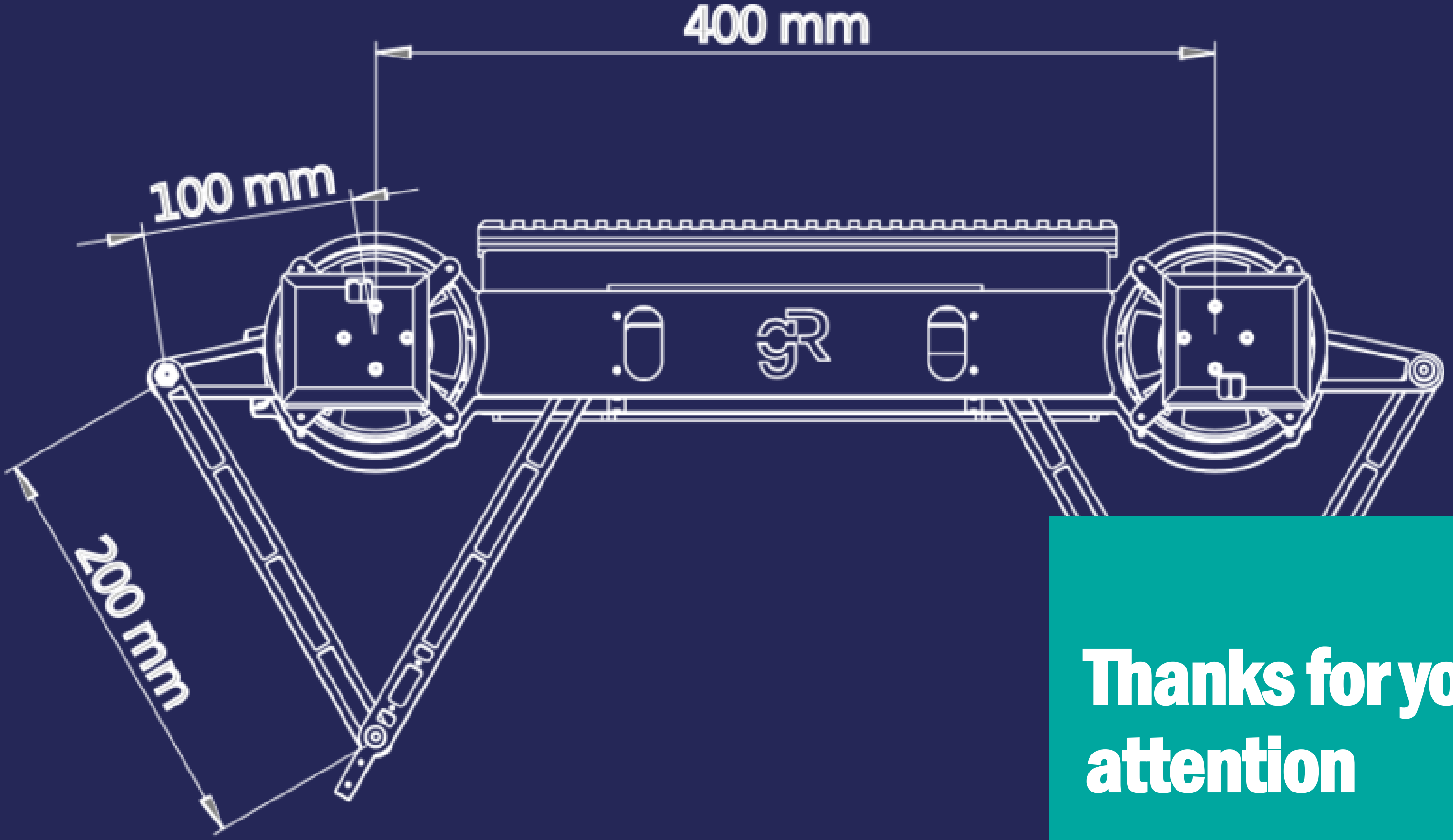
Particular impact:

- The paper marks a **turning point** in legged robotics, proving that **direct-drive designs are viable** for dynamic locomotion.
- Introduced metrics ($K_{ts}$, $\mathrm{a}_{\mathrm{mcv}}$ ) are now design references in legged robot actuation.

Criticism:

- **Scalability**: focus on relatively small robots (2–5 kg) ⟶ non-trivial to scale the direct-drive paradigm to larger payloads
- **Torque/ force density limitations**: development of quasi-direct-drive
- **Energy efficiency at low speed**: at low speeds or in quasi-static situations, geared/compliant actuators may still outperform direct-drive in energy use

https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8794436
https://www.frontiersin.org/journals/robotics-and-ai/articles/10.3389/frobt.2018.00129/full




# Thanks for your attention