

# Selective Torque Support Mechanism: Passive-Switching Torque Compensation Mechanism for Legged Robots

Gihyeok Na, Filip Bjelonic, Victor Klemm, Giorgio Valsecchi, and Marco Hutter

**Abstract**—Recent years have shown numerous applications of legged robots where efficient locomotion is crucial for increased range or payload capabilities. As leg actuators must apply a static torque to compensate for the robot’s weight most of the time, adding parallel elastic elements joints can enhance energy efficiency and strength by providing additional torque support to actuators. However, simply adding parallel elastic elements to legs generates torque even when unnecessary, hindering further performance improvement. We propose the Selective Torque Support (STS) mechanism to address this. It selectively supports torque by engaging a spring only in a range of specific joint angles when the leg bears the robot’s weight. Implementable in the thigh, the STS mechanism features a simple structure and operates passively. We evaluate the optimal design using fine-tuned locomotion policies trained via reinforcement learning to determine its performance in diverse simulation environments. The simulation results indicate that the proposed mechanism enhanced the robot’s averaged torque squared (winding losses) by 43 % compared to the baseline without compromising tracking performance during forward walking on flat terrain. Also, it yielded 39 % and 33 % improvements in averaged torque squared on uneven sloped and obstacle terrain, respectively. We further built a demonstrator to validate the working principle in the real world.

## I. INTRODUCTION

Quadruped robot design efficiently distributes weight across all four legs, allowing them to carry heavy payloads. This utility is valuable for transporting goods, equipment, or injured individuals in environments where wheeled or tracked robots may struggle. Enhancing energy efficiency in quadruped robots remains a significant challenge, as they currently lag behind animals [1]. Actuation systems and driving leg movements notably impact energy consumption. The knee joint bears a substantial portion of the robot’s weight. By minimizing the torque requirements at the knee joint, the overall energy efficiency of the robot can be improved.

This study introduces a novel concept of a passive-switching torque compensation mechanism to enhance energy efficiency in legged robots. We validate the mechanism’s impact on energy efficiency during locomotion by integrating it into a quadruped robot and conducting tests across various simulation environments. Furthermore, we ensure its real-world applicability by building a full-scale model and performing stress analysis.

This work has been created in the scope of a Master’s Thesis by Gihyeok Na. All other authors were in a supervising role.

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## A. Legged Robots with Parallel Elastic Actuators

Employing elastic elements in parallel with actuators, known as Parallel Elastic Actuators (PEAs), can passively support additional torque to a joint [2], [3]. This approach offers advantages in terms of energy efficiency by reducing power and torque requirements for actuators, resulting in improved overall system efficiency. STEPPR [4] has parallel elastic springs at its hip and ankle joints. During walking, the utilization of only the hip spring leads to a 31 % reduction in joint electrical power. SpaceBok [5] incorporates parallel elastic elements in its leg, of which kinematics are based on a parallelogram mechanism, enabling powerful jumping maneuvers. Tachyon [6] utilizes Serial-Parallel Elastic Actuators (SPEAs) to achieve high payload capacity and improved energy efficiency. Implementing SPEAs resulted in substantial power consumption reductions, ranging from 5 % to 33 %. In [7], the quadruped robot ANYmal [8] is fitted with parallel elastic elements in the knees, achieving a 33 % improvement in torque square efficiency and a 30 % reduction in maximum torque. Ascento [9], a jumping-wheeled-legged robot, is equipped with torsion springs at its knee joint to counteract the robot’s weight.

One drawback of PEAs lies in their consistent torque support on the knee joint throughout all gait phases, as described in Figs. 1(a)(b). While PEAs provide beneficial torque support during the stance phase to counteract gravity when the leg bears weight (Fig. 1(a)), this support becomes counterproductive during the swing phase (Fig. 1(b)). Here, with the leg in the air, the knee actuators need to counteract the torque generated by the PEAs (Fig. 1(c)), leading to additional energy consumption during this phase and limiting further energy efficiency enhancement.

## B. Selective Torque Support

To address the limitations of PEAs, the concept of a clutched PEA was proposed [10]. This approach involves an electric clutch-controlled parallel spring. Another proposed solution [11], [12] is to equip a PEA with a torsion spring that can store kinetic energy at any joint position. The spring is mounted between two outgoing axes of a differential mechanism. However, both methods require actuator redesign or additional active components, significantly increasing complexity. Furthermore, a switching PEA [13] for the knee has been proposed, but it requires an extra actuator and a complete legged system redesign. Birdbot [14] utilizes a self-engaging and disengaging parallel elastic leg mechanism. This mechanism employs a pulley and multi-articular tendon released and slackened by the foot’s lever action. The

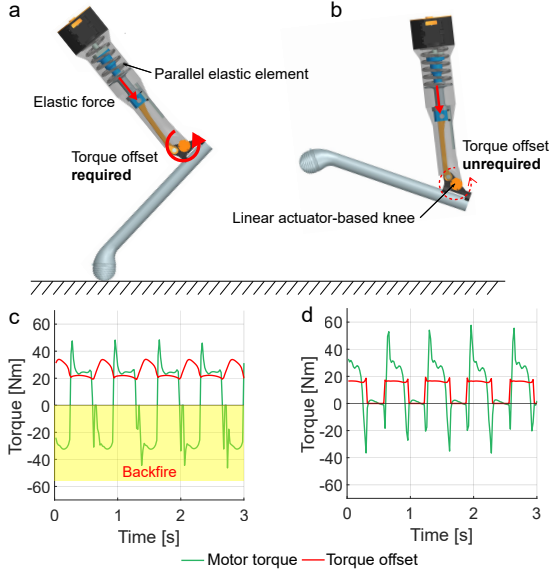


Fig. 1. (a) The knee is extended during the stance phase, where the leg bears the robot's weight. The parallel elastic element supports the actuator by generating a torque offset that counters gravity. (b) The knee is flexed during the swing phase, where the leg is in the air. The parallel elastic element still generates torque offset that is counterproductive. (c) A PEA provides torque support to the knee even during the swing phase, necessitating the motor to counteract it, which leads to additional power consumption. (d) The proposed mechanism selectively supports torque on the knee during the swing phase, resulting in further improvements in energy efficiency.

clutched knee actuator enables less than 10 % of knee-flexing torque. However, this mechanism cannot be applied in legged systems without feet. In [15], a switching mechanism for engaging a parallel elastic element by crossing the singularity of the leg was introduced, resulting in a 40 % reduction in average knee actuator torque during a hopping. Nevertheless, this design requires a reconfigurable leg and may not be compatible with legged systems employing linear actuator-based knees.

Furthermore, the concept of selective torque support also holds value for wheeled-legged systems. It allows for the use of elastic elements with higher stiffness to support greater payloads in such systems, which might be unsuitable for stepping without this feature.

### C. Contribution

We introduce the concept of a passive-switching torque compensation mechanism for legged robots, named Selective Torque Support (STS) mechanism. Our approach does not necessitate any redesign of actuators or the legged system, highlighting its straightforward structure and entirely passive operation. It focuses on a specific knee joint angle range during the gait phase. This mechanism is designed to generate additional torque solely within this knee joint angle range, effectively supporting the knee actuator only during the stance phase (Fig. 1(d)). Additionally, we validate the performance of the proposed mechanism through simulation experiments. Our main contributions are:

- Introduction of a novel passive-switching PEA for

legged systems.

- Quantitative performance evaluation of the mechanism in simulation environments.
- Stress analysis for demonstration of feasibility.
- Design of a functional full-scale demonstrator.

## II. METHOD

This section introduces the design of the PEA mechanism and its operational principle. We outline our approach to optimize the controller via Reinforcement Learning (RL) that is needed for the design optimization (pre-trained policy) and performance evaluation (fine-tuned policy), as well as design parameters optimization. We denote  $\mathbf{d}$  as design parameters,  $\tau$  as the torque on the knee joint, and  $q_{\text{KFE}}$  as the knee joint angle. Vectors and matrices are marked in bold text.

### A. Design Concept

The proposed mechanism achieves the engagement or disengagement of the parallel elastic element from the system through the passive conversion of linear motion into rotational motion. Its working principle possesses some similarities to clicking mechanisms in ballpoint pens. Fig. 2(a) shows components of the STS mechanism: a grooved element, a cylindrical cam, a spring interface, and a spring. The spring interface attaches to the linear slider, transmitting elastic force to the link. The cylindrical cam determines the switching point  $q_{\text{KFE}}^*$ .

Fig. 2(b) illustrates the working principle of three main repeatable steps. Since the position of the linear slider  $q_{\text{lin}}$  determines the knee joint angle in a linear actuator-based knee configuration (i.e.,  $q_{\text{KFE}}(q_{\text{lin}})$ ), each step is linked to the position of the linear slider.

Each steps are proceeds as follows (Fig. 2(b)):

- 1)  $q_{\text{KFE}} < q_{\text{KFE}}^*$ : The spring is disengaged from the system, resulting in no torque offset.
- 2)  $q_{\text{KFE}} = q_{\text{KFE}}^*$ : The spring engages or disengages from the system.
- 3)  $q_{\text{KFE}} > q_{\text{KFE}}^*$ : The spring is engaged with the system, generating torque offset at the knee joint.

The torque offset generated by the STS mechanism, denoted as  $\tau_{\text{off}}$ , is modeled as

$$\tau_{\text{off}}(q_{\text{KFE}}; \mathbf{d}) = \tau'_{\text{off}}(q_{\text{KFE}}; \mathbf{d})H(q_{\text{KFE}} - q_{\text{KFE}}^*) \quad (1)$$

where

$$H(q_{\text{KFE}} - q_{\text{KFE}}^*) := \begin{cases} 1 & \text{if } q_{\text{KFE}} - q_{\text{KFE}}^* \geq 0 \\ 0 & \text{if } q_{\text{KFE}} - q_{\text{KFE}}^* < 0 \end{cases} \quad (2)$$

and  $\tau'_{\text{off}}$  represents the torque offset caused by the spring in the absence of the STS mechanism.

### B. Locomotion Policy Training

An optimal controller is essential to assess a design's peak performance. We employ RL [16] to train locomotion policies based on the assumption that a neural network policy can achieve a high level of locomotion skill [17].

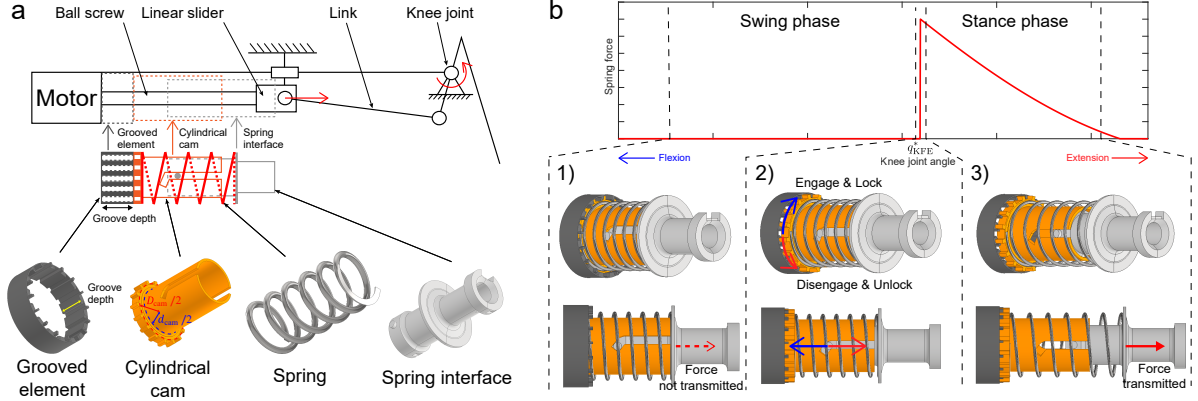


Fig. 2. (a) The STS mechanism is implemented in the thigh of the legged robot with linear actuator-based knees. It comprises four parts: a grooved element, a cylindrical cam, a linear spring, and a spring interface. (b) illustrates three operational principle steps. 1) The cylindrical cam is engaged with the grooved element and moves with the spring interface (linear slider). 2) The linear motion of the spring interface causes the cylindrical cam to rotate and (dis)engage with the grooved element, converting the elastic force into an external force. 3) The cylindrical cam is disengaged from the grooved element and rests atop the grooved element. The elastic force is transmitted to the link, supporting additional torque to the knee joint.

We train two distinct locomotion policy types: pre-trained and fine-tuned policy for design optimization. The pre-trained policy is trained without any PEA setup and is subsequently deployed to the agent (robot) without any PEA configuration. We collect data for design optimization using this policy, as outlined in Section II-C. The fine-tuned policy is trained for each PEA design configuration with the obtained design parameters and is deployed to the agent with the corresponding PEA setup.

We utilize Legged Gym [18], the Isaac Gym [19] environments for legged robots as our RL platform. The reward function  $r$  includes metrics for tracking command velocities, penalizing undesired base velocities. We utilize an identical reward setup to train all agents in the comparison group, described in Sec. III-B.2. This approach is adopted because the cumulative reward (3) assesses and compares the subjects' overall performance.

$$\sum_{t=0}^T \gamma^t r(a_t, s_t) \quad (3)$$

where  $\gamma \in [0, 1]$  is the discount factor.

### C. Design Optimization

We outline our approach for optimizing the design parameters. We collect data from the configuration without PEAs to define the objective function  $f$ . Using the model for the torque offset  $\tau_{\text{off}}$ , determined by design parameters  $\mathbf{d}$ , the objective function can be formalized.

1) *Design Objective*: Our primary design objective is to enhance the robot's energy efficiency. Given the difficulty of accurately simulating a robot's energy efficiency, we assume that the resistive power loss of motors, a significant contributor to overall motor losses, can reasonably approximate the total energy consumption. While there are other factors to consider, such as electronics and transmission loss, we assume to simplify our analysis that their impact is relatively minor and negligible when compared to the resistive power

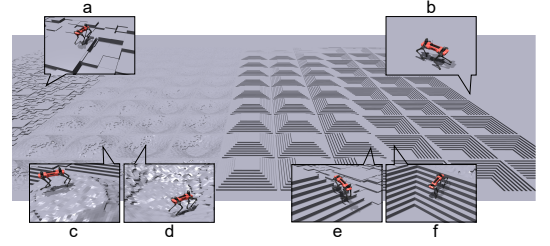


Fig. 3. Various terrain types in the simulation environments: (a) randomized and discrete obstacles, (b) flat terrain, (c)(d) uneven sloped terrain, and (e)(f) stairs.

loss of motors. We define the Cost of Torque (CoTr) similar to the Cost of Transportation (CoT) [7].

$$\text{CoT} \propto \text{CoTr} := \frac{1}{mg\Delta s} \int_0^T \tau_{\text{motor}}^2 dt \quad (4)$$

$$= \frac{\tau_{\text{motor}}^2 T}{mg\bar{v}T} = \frac{\tau_{\text{motor}}^2}{mg\bar{v}} \quad (5)$$

Where  $\tau_{\text{motor}}$  is the motor torque.

Given that  $\bar{v}$  and  $g$  are out of control, minimizing  $\tau_{\text{motor}}^2$ , the Mean Squared Torque (MTS), consequently leads to a decrease in the CoT. Here, we exclude the total mass of the STS mechanism, as explained in Sec. III-B.

2) *Parameter Optimization*: The design space  $\mathbf{d} \in \mathcal{D}$  is defined as  $\mathbf{d} \in [N_a, D_o, D_w, L_0, q_{\text{KFE}}^*]^T$ , where  $N_a, D_o, D_w$ , and  $L_0$  represent linear spring design parameters: the number of active coils, outer diameter, wire diameter, and free length, respectively. To determine the optimal design parameters  $\mathbf{d}^* \in \mathcal{D}$  for a specific task  $t \in \mathcal{T}$ , with a given pre-trained policy  $\pi_{\theta}^0$ , the objective function  $f(\mathbf{d}|t, \pi_{\theta}^0) : \mathcal{T} \times \mathcal{D} \rightarrow \mathbb{R}$  is defined. The objective function  $f$  assesses design parameters  $\mathbf{d}$  for a particular task  $t$  and produces a performance metric as its output. Here, the task  $t$  is tracking randomized velocities with a specific payload on various terrain types (Fig. 3), which is solved by the pre-trained policy  $\pi_{\theta}^0$ .

As discussed in Sec. IV-A, we assume that minimizing MTS leads to improved energy efficiency. Therefore, our objective is to minimize MTS, which is expressed as:

$$\overline{\tau_{\text{motor}}} = \frac{1}{N} \sum_{i=1}^N \tau_{\text{motor},i}^2 \quad (6)$$

where  $i$  represents the  $i$ th sample of data and  $N$  is the total number of samples.

For the problem generalization and computational efficiency, we estimate the Probability Density Function (PDF)  $P(q_{\text{KFE}}, \tau|t, \pi_{\theta}^0)$  by fitting a Gaussian Mixture Model (GMM) to data collected from 1000 episodes.

By incorporating the object mentioned above and the estimated PDF  $P$ , we then define the objective function  $f$  as

$$\iint [\tau - \tau_{\text{off}}(q_{\text{KFE}}; \mathbf{d})]^2 P(q_{\text{KFE}}, \tau|t, \pi_{\theta}^0) dq_{\text{KFE}} d\tau \quad (7)$$

The optimization problem can then be formalized as

$$\mathbf{d}^* = \arg \min_{\mathbf{d} \in \mathcal{D}} f(\mathbf{d}|t, \pi_{\theta}^0) \quad (8)$$

$$\text{s.t. } \mathbf{c}(\mathbf{d}) = \begin{bmatrix} \mathbf{c}_{\text{design}} \\ \mathbf{c}_{\text{morph}} \\ \mathbf{c}_{\text{safety}} \end{bmatrix} \preceq \mathbf{0} \quad (9)$$

where

$$\mathbf{c}_{\text{design}} = \begin{bmatrix} C(D_o, D_w) - 12 \\ 6 - C(D_o, D_w) \\ N_a - 15 \\ 4 - N_a \\ p(N_a, L_0, D_w) - 0.5D_m \\ 0.8 - \frac{L_0}{D_m} \\ \frac{L_0}{D_m} - \frac{\pi}{\alpha} \left[ \frac{2(E - G)}{2G + E} \right]^{1/2} \end{bmatrix} \quad (10)$$

$\mathbf{c}_{\text{design}}$  is related to design of the linear spring. The first and second elements are feasibility conditions regarding the spring index, the third and fourth ones regarding the number of active coils, the fifth one regarding pitch, the sixth aspect ratio, and the seventh stability without buckling [20].  $D_m = D_o - D_w$ ,  $\alpha = 0.5$ .  $C$ ,  $p$ ,  $E$ , and  $G$  denote the spring index, spring pitch, Young's modulus, and shear modulus of the material, respectively.

$$\mathbf{c}_{\text{morph}} = \begin{bmatrix} D_o - D_{\text{cam}} \\ d_{\text{cam}} - (D_o - 2D_w) \end{bmatrix} \quad (11)$$

$\mathbf{c}_{\text{morph}}$  constrains the morphology of parts of the STS mechanism to be installed inside the thigh.  $D_{\text{cam}}$  and  $d_{\text{cam}}$  are shown in Fig. 2.

$$\mathbf{c}_{\text{safety}} = \begin{bmatrix} n_s - \frac{S_y(D_w)}{S_{\text{max}}(N_a, L_0, D_o, D_w)} \\ L_0 - L_{\text{lim}} \end{bmatrix} \quad (12)$$

$\mathbf{c}_{\text{safety}}$  ensures the safety of the STS mechanism. The first element prevents plastic deformation of the spring. The

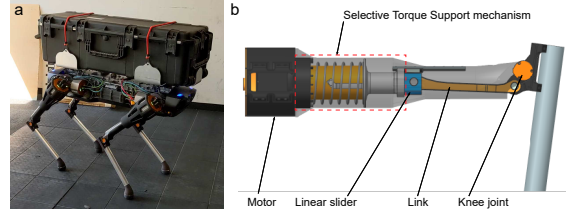


Fig. 4. (a) Overview of the quadruped robot used as the platform for this study. [21] (b) The STS mechanism is installed within the robot's thigh. The CAD view shows the mechanical components.

TABLE I  
OVERALL SPECIFICATIONS OF THE PLATFORM ROBOT

|                                            |             |
|--------------------------------------------|-------------|
| Leg size [m]                               | 0.8         |
| Total mass [kg]                            | 48          |
| Power [W]                                  | 370         |
| Energy [Wh]                                | 930         |
| Max. Payload [kg]                          | 90          |
| Peak torque of the knee actuator [Nm]      | 150*, 450** |
| Max. velocity of the knee actuator [rad/s] | 18*, 6.0**  |

\* Fully folded.

\*\* Max. gear ratio.

second element, which includes  $L_{\text{lim}}$ , ensures that the spring is not pre-tensioned.  $S$  and  $S_y$  represent the spring's torsional stress and the material's yield strength, respectively. The yield strength  $S_y$  can be approximated using  $D_w$  [20]. A safety factor of  $n_s = 1.4$  is employed.

We utilize the Genetic Algorithm (GA) for solving the optimization problem, given that  $N_a \in \mathbb{N}$ .

### III. EXPERIMENTS

In this section, we introduce the setup for a simulation experiment to evaluate the STS mechanism's performance. We first describe the legged robot platform used for implementing the proposed mechanism. Lastly, Sec. III-C details the methods used to validate its feasibility and real-world applicability.

#### A. Legged Robot Platform

We utilize the quadruped robot Barry (Fig. 4) [21] as the platform for implementing the proposed mechanism. As shown in Fig. 4(b), ball screws actuate the robot's knee joints. Further details about the robot's specifications can be found in Tab. I.

#### B. Simulation Setup

We assess the performance, focusing on two key factors: improvement of energy efficiency and maintenance of other performance factors such as tracking velocities. Both factors are quantified and compared within the comparison group. To validate the performance of the STS mechanism, we compare these metrics not only with the baseline setup (without any PEA) but also with four subjects with parallel elasticities without the STS mechanism. Given that the total mass of the STS mechanism is relatively small at  $0.9 \times 4 = 3.6$  kg (assuming the parts material is Al6061-T6 and spring

material is ASTM A229), we disregard it considering the overall mass of the robot, which is close to 50 kg.

The agent tracks a command velocity with a specific payload on various terrain types. Secs. III-B.3 and III-B.4 include tasks and terrain setup details for the evaluation.

1) *Evaluation Metrics*: We employ two primary metrics to evaluate the performance:

- **Mean Squared Torque (MTS)**: PEAs aim to enhance energy efficiency. As elucidated in Sec. II-C.1 and (5), we assume that minimizing this metric is directly correlated with reducing energy consumption. A lower MTS indicates higher energy efficiency. For easy comparison, we use normalized MTS as follows:

$$\frac{\overline{\tau_{\text{motor}}^2}}{\tau_{\text{motor, base}}^2} \quad (13)$$

where base represents the baseline configuration.

- **Mean Reward (MR)**: The overall performance can be assessed by the cumulative reward (3) during simulation. MR is defined as

$$\bar{r} = \frac{1}{T} \sum_{t=0}^T \gamma r(a_t, s_t) \quad (14)$$

A lower MR indicates a compromise of other performances, including tracking performance. We use normalized MR as follows:

$$\frac{\bar{r}}{r_{\text{base}}} \quad (15)$$

2) *Comparison Group*: The comparison group comprises without any PEA (baseline) and PEAs configurations. For PEAs configuration, we employ four agents with optimized springs without the STS mechanism and optimized design with the STS mechanism.

Each agent has a fine-tuned policy, individually trained for their respective configurations, as detailed in Sec. II-B. Deploying these fine-tuned policies to each subject enables the comparison of peak performances.

3) *Tasks*: We employ the following tasks for evaluation:

- Payloads [kg]: 0, 5, 15, 22, 40, 55, 72, 85, 92
- Command velocities [x m/s, y m/s, yaw rad/s]
  - Forward walking: [0.2, 0.0, 0.0], [0.7, 0.0, 0.0], [1.2, 0.0, 0.0]
  - Backward walking: [-0.7, 0.0, 0.0]
  - Side walking: [0.0, 0.7, 0.0]
  - Diagonal walking: [0.7, 0.7, 0.0]

4) *Terrain*: The robot should maintain versatility, one of the most critical features of legged robots. We utilize four types of terrains: flat terrain, stairs, randomized and discrete obstacles, and uneven sloped terrain, as shown in Fig. 3. On flat terrain, the agent tracks various command velocities, each with different payloads. In contrast, considering the most typical scenario, we set the agent to track only one command velocity on rough terrain, forward walking at 0.7 m/s

### C. Feasibility

Ensuring the viability of the proposed mechanism is paramount, even though we primarily conduct the experiments in simulation environments. Transferability to the real world can be demonstrated through stress analysis and functionality. The mechanism's components must show sufficient durability during operation, and it should function without malfunctions.

1) *Stress analysis*: All parts must have sufficient durability to prevent catastrophic fractures during operation. Among these, the lugs of the cylindrical cam, which contact the surface of the groove, are particularly vulnerable. We conduct a stress analysis of the cylindrical under maximum spring force configuration and validate the durability of the STS mechanism during operation using Finite Element Analysis (FEM).

2) *Mockup*: The full-scale model demonstrates the mechanism's applicability in the real world. We fabricate the parts by Fused Deposition Modeling (FDM). Additionally, we incorporate transparent acrylic pipes for the thigh housing to allow visibility into the internal structure. While the actual components, including the link, linear slider, linear bearing, and knee actuator (see Fig. 4(b)), are retained, we opt for a commercially available spring with lower stiffness due to cost and durability considerations.

## IV. RESULTS

Before reporting the results of our simulation experiments, we first present the obtained design parameters  $\mathbf{d}^*$  and validate the feasibility of the STS mechanism. Next, we present the results of our simulation experiments, aiming to validate the effectiveness of our approach. We analyze these results using the quantitative metrics described in Sec. III-B.

### A. Optimal Design Parameters

The obtained optimal parameters  $\mathbf{d}^*$  are

$$\mathbf{d}^* = [5, 74.0 \text{ mm}, 8.1 \text{ mm}, 124.0 \text{ mm}, -1.59 \text{ rad}]^T \quad (16)$$

We used a diverse payload task setup, including a payload of 10, 20, 50, 70, and 90 kg for parameter optimization of the STS mechanism. However, each optimal design for these setups did not show significant performance differences. Unlike the trade-off with spring stiffness for PEAs without the STS mechanism, where higher stiffness provides more torque offset and results in higher counteraction, the STS mechanism is free from this trade-off. Therefore, the spring design parameters for each setup do not vary significantly and tend to converge toward maximizing spring stiffness.

### B. Feasibility

1) *FEM*: With the optimal design parameters, the maximum force applied to the cylindrical cam is less than 1200 N. Specifically, the lugs of the cylindrical cam, the most vulnerable part, have been evaluated. The FEM assuming the material used is Al6061-T6 results under the maximum spring force setup confirm the cylindrical cam's durability during operation.

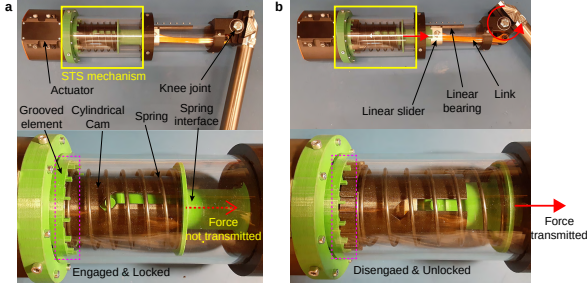


Fig. 5. The full-scale model of the STS Mechanism. Mechanism components are 3D printed, and transparent acrylic pipes were utilized for the thigh housing. (a) There is no torque offset when  $q_{KFE} < q_{KFE}^*$ . (b) Torque offset is generated when  $q_{KFE} > q_{KFE}^*$ .

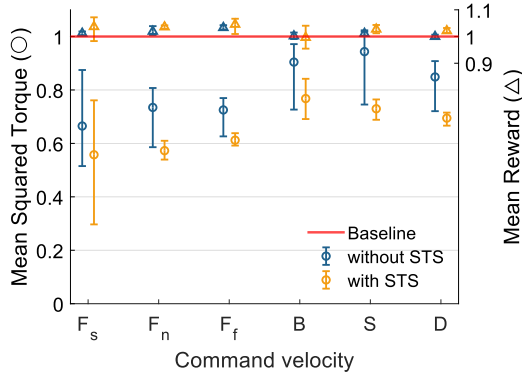


Fig. 6. This graph displays the maximum, average, and minimum values of MTSs and MRs across all tested payload setups on flat terrain. The command velocity abbreviations are as follows: **F**orward, **B**ackward, **S**ide, and **D**iagonal walking. The subscript represent: **s**low (0.2 m/s), **n**ormal (0.7 m/s), and **f**ast (1.2 m/s).

2) *Functional Test*: We validated the working principle by constructing and using a functional mockup. Fig. 5 displays the mockup in both steps 1) and 3), as described in Sec. II-A and Fig. 2(b). This full-scale model demonstrates smooth operation without significant issues, indicating the absence of the critical problems in the STS mechanism's working principle.

### C. Simulation Experiments

We report the results of our simulation experiments, which involved collecting data from 400 different episodes for each simulation environment. For clarity, we have included only the data from the individual best-performing subject for each test in the comparison group in the following graphs.

1) *Flat Terrain*: Fig. 6 demonstrates a significant decrease in MTSs with the STS mechanism, accompanied by generally increased MRs. This reduction indicates substantial energy efficiency enhancement without sacrificing overall performance across various command velocities. Notably, the STS mechanism outperformed all subjects in the comparison group without it. Specifically, in the forward walking setup, the STS mechanism achieved average MTS reductions of 45 %, 43 %, and 39 % compared to the baseline at speeds of 0.4 m/s, 0.7 m/s, and 1.2 m/s, respectively.

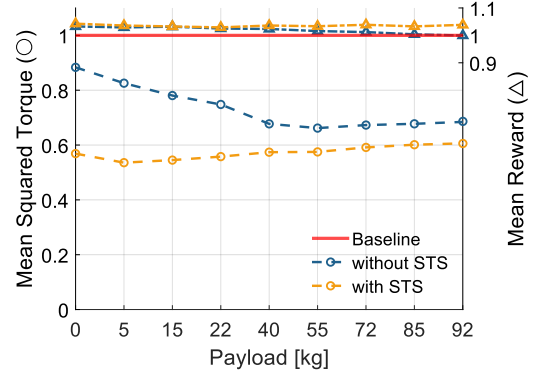


Fig. 7. MTSs and MRs for payloads under the forward walking (0.7 m/s) setup.

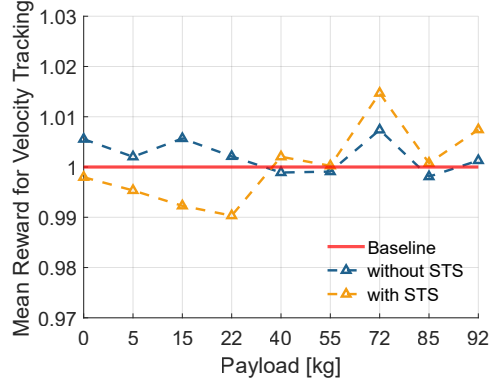


Fig. 8. MRs for velocity tracking for payloads under the forward walking (0.7 m/s) setup.

As depicted in Fig. 7, the STS mechanism significantly outperformed in the specific payload range ( $< 40$  kg). Under zero payload conditions, the STS mechanism reduced MTSs by 44 % compared to the baseline, while the best-performing subject reduced it by only 12 %. In Fig. 8, both subjects exhibited negligible compromise in tracking performance, with reductions in MRs for velocity tracking of less than 1 % compared to the baseline for some payload setups.

2) *Rough Terrain*: We conducted tests using the forward walking setup at a speed of 0.7 m/s on four types of terrain (see Fig. 3). Fig. 9 illustrates the performance comparison across these terrain types, consistently showing the STS mechanism outperforming all other subjects.

On uneven slopes and randomized obstacles, the STS mechanism achieved an average MTS reduction of 39 % and 33 % compared to the baseline, with no significant compromise in MRs. On stairs, the best-performing subject in the comparison group only achieved a negligible average MTS reduction of 2 %, whereas the STS mechanism reduced it by 13 %. Notably, we observed the most significant compromise in overall performance on stairs. The STS mechanism reduced MRs by an average of 20 %, while the other subject reduced it by 19 %. This fact suggests that all subjects had considerable performance trade-offs when navigating stairs, particularly in tracking performance.

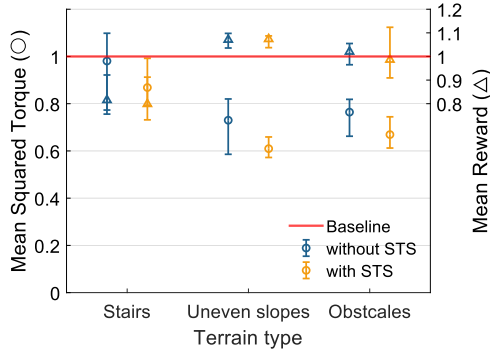


Fig. 9. This graph shows the maximum, average, and minimum values of MSTs and MRs on three types of rough terrain. The tests were conducted under a forward walking setup at 0.7 m/s.

## V. CONCLUSION

We introduced a novel passive-switching torque compensation mechanism designed to tackle the issue of PEA and demonstrated its effectiveness through simulation experiments. Notably, we achieved switching by (dis)engaging the spring within the system using a simple mechanism, which is an intriguing aspect of our approach. While the core idea of this approach, supporting torque within a specific range of joint angles proves beneficial, it may only encompass some possible scenarios. For instance, when a robot is crouched, causing the knee joint angle to deviate from the designed range, the STS mechanism cannot provide the necessary torque support, which is undesirable. To comprehensively address this challenge, an active-switching PEA, such as a torque-activated mechanism, without relying on a passive-switching approach can be contemplated. However, to the best of our knowledge, no such mechanism for legged robots has been proposed, and incorporating such a mechanical system into the leg could present significant challenges, necessitating solutions for various accompanying problems.

It is crucial to recognize that this mechanism's exact effectiveness and productivity remain uncertain due to the absence of hardware experiments. Discrepancies between simulation and reality can arise due to unaccounted factors such as mechanical losses or other energy consumption. Moreover, it is essential to acknowledge that the proposed mechanism may introduce additional dynamic frictions to the system, a factor that was not accounted for in our experiments. The added complexity leads us to anticipate that the actual performance may be inferior to what was observed in the simulation experiments.

Future work will encompass hardware testing and enhancements to adapt the mechanism to various scenarios, including transforming the robot's stationary posture. Additionally, we will explore the co-optimization of the controller and design parameters. It will involve utilizing methods such as [7] to achieve higher performance levels.

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