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Preloaded Hopping with Linear Multi-Modal Actuation

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Abstract— **For more dexterous and agile legged robot locomotion, alternative actuation has been one of the most long-awaited technologies. The goal of this paper is to investigate the use of newly developed actuator, the so-called Linear Multi-Modal Actuator (LMMA), in the context of legged robot locomotion, and analyze the behavioral performance of it. The LMMA consists of three discrete couplings which enable the system to switch between different mechanical dynamics such as instantaneous switches between series elastic and fully actuated dynamics. To test this actuator for legged locomotion, this paper introduces a one-legged robot platform we developed to implement the actuator, and explains a novel control strategy for hopping, i.e. "preloaded hopping control". This control strategy takes advantage of the coupling mechanism of the LMMA to preload the series elasticity during the flight phase to improve the energy efficiency of hopping locomotion. This paper shows a series of experimental results that compare the control strategy with a simple sinusoidal actuation strategy to discuss the benefits and challenges of the proposed approach.**

I. INTRODUCTION

The musculoskeletal body plan of biological systems provide a number of different ways to control their bodies such as precise positioning of body parts, fast repetitive motions, preloading for instantaneous high-jumps, and damped passive walking on a slope. In contrast, our robots are still severely constrained by the limitation of actuator technologies as most of our legged robots are controlled through either fully actuated or completely passive joint operations.

In order to relax the significant demand of new actuation technologies, a few different approaches were previously proposed to for legged robot locomotion. One of the most popular approaches is to employ the Series Elastic Actuator (SEA) in the joints of legged robots [1]. The SEA is an actuator that equips with a mechanical spring in series to mimic the viscoelastic properties of biological muscles [2]. A number of advantages have been reported for this approach, as it can be used to store kinetic energy in the mechanical springs for energy efficient motor control [3], [4], to achieve precise force control without expensive force sensors, and to filter instantaneous impacts without high control bandwidth. Even though the dynamic range of motor operation is generally limited [1], [5], the concept has also been extended to many other configurations of mechanical springs to identify how they can contribute to different dynamic motion control of robotic systems [6], [7]. More recently, a number of researchers have been developing mechanisms to vary elasticity on the fly such that variations of mechanical dynamics can be achieved in the legged robot locomotion, for example [9], [10], [11], [12]. These actuators aim to have the benefit of both compliance when it is required but also the ability to adjust the stiffness of the system to increase the bandwidth of the actuator or to match the actuator's resonant frequency to the task [11], [13]. Humans and animals have also been shown to regulate the stiffness of their legs to match the speed at which they are running [14]. These actuators have been implemented and tested in the legged robot locomotion to investigate specific advantages such as energy efficiency over different locomotion speeds, for example. There are also a number of different actuator technologies being developed [15] although it still requires some additional investigations to fully clarify how they can be used in legged robot locomotion and what would be the benefits.

From this perspective, we have been developing an alternative actuation technology, the so-called Linear Multi-Modal Actuator (LMMA)[8]. Based on the small-sized discrete couplings that can generate relatively large holding forces, the actuator is capable of instantaneously switching between different mechanical dynamics including complete passive dynamics, to series elastic and fully actuated joint operation. While the performance of this actuator seems to be promising, it has not been clarified how this technology can be used in the context of legged locomotion and how locomotion can benefit from it. From this perspective, the goal of this paper is to propose a control strategy of one-leg hopping robot, that is, "preloaded hopping control", that takes advantage of the discrete coupling of LMMA. The control strategy is also tested in the real-world hopping experiments to discuss the benefits and challenges of the proposed approach with respect to a conventional hopping control based on the series elastic actuator.

We structure the rest of the paper as follows. Section II describes the mechanisms and designs of the LMMA and the robot platform, and the hopping control strategies are explained in Section III. Section IV shows the results of the hopping experiments, and Section V concludes the paper with some remarks on future works.

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II. EXPERIMENTAL PLATFORM

To explore the use of the new actuation technology, we developed a planar one-legged robot (Fig. 1) that is able to accommodate the LMMA for systematic experiments. This section first introduces the basic characteristics of LMMA,

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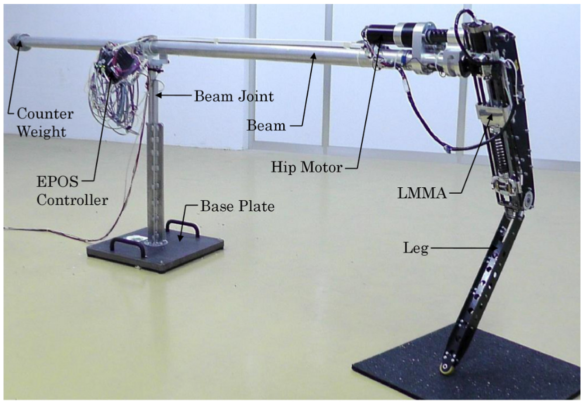

Fig. 1. Picture of the ETHOP robot.

and then explains how we implemented the actuator in the platform.

A. Linear Multi-Modal Actuator

The LMMA was developed to investigate the use of small-size discrete couplings in robot motion control, and we introduced the basic concept of multi-modal actuation in which how a series of discrete couplings could provide a variety of mechanical dynamics for versatile joint operations in robotic application [8]. Fig. 2 show one of the prototype which consists of three discrete couplings (labeled as brakes) mounted on three slides which are aligned on a pair of parallel rails. Every coupling is controlled by a brake motor (modified from KONDO KRS 2350 HV) that engages or disengages the brake pads such that the slide can be fixated or released with respect to the brake rails. By including or excluding active/passive components between these slides, the LMMA is capable of dynamically configure different mechanical dynamics between the front and back Mounting points such as fully actuated or series elastic dynamics.

In our previous investigation, we demonstrated that the LMMA is capable of generating eight different operation modes as shown in Table I. For example, when all couplings are disengaged (indicated by "0" in Table I), the LMMA exhibits completely passive dynamics, while it becomes fully actuated when the center coupling is engaged (indicated by "1"). In the active mode, a direct drive of the joint can be realized by using the ballscrew motor shown in Fig. 2(b) (MAXON RE40, #148877). In contrast, the series elastic mode includes a compliant element between motor and joint by engaging the front coupling, and disengaging the other two. And finally, in the control strategy we introduce in the next section, we also employ another mode, labeled "preload", which engage both front and motor couplings to store energy without moving the joint. During the experiments, we used the series elastic and the preload mode to realize the desired hopping patterns.

B. ETH HOPING ROBOT

The ETH Hopping Robot (ETHOP, Figure 1) was developed specifically for the purpose of systematic investigation of the performance of LMMA in the context of hopping locomotion. The platform consists of a stand, a beam, a set of counter-weight, a hip motor, and a two-segment leg equipped with the LMMA. The technical specifications of the robot is shown in table II and the dimensions are illustrated in figure 3.

The leg structure shown in Fig. 2(c) has two segments (thigh and shank in the figure) that are connected through a knee joint. The segments are mainly made of carbon-fibre, and a passive wheel is installed at the end of shank segment, which allows the entire leg sliding lateral direction during stance phases. In parallel to the thigh segment, the LMMA is implemented where the front mounting point of

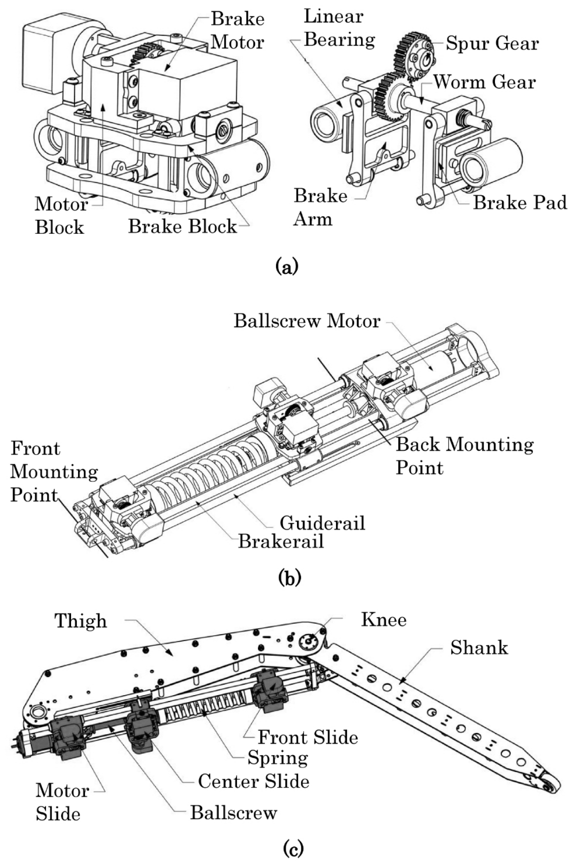

Fig. 2. CAD Pictures of the LMMA brake mechanism (a), the actuator itself (b) and the implementation in the robot leg (c).

TABLE I
OPERATION MODES OF THE LMMA DEPENDING ON THE STATES OF THE THREE COUPLING SLIDES.

Coupling slide			
Front	**Center**	**Motor**	**Mode**
0	0	0	Passive
0	0	1	Rigid
0	1	0	Active
0	1	1	Transition
1	0	0	Series elastic
1	0	1	Preload
1	1	0	Store
1	1	1	Transition

TABLE II

TECHNICAL DATA OF THE ETHOP

Parameter	Value	Parameter	Value
l_{thigh}	600 mm	$l_{kneelever}$	70 mm
m_{thigh}	1100 g	$\varphi_{kneelever}$	32°
Θ_{thigh}	$[2.5, 118.2, 119.5]^T \cdot 10^3 kg \cdot mm^3$	$l_{x,BMP}$	92 mm
l_{shank}	640 mm	$l_{y,BMP}$	56 mm
m_{shank}	620 g	l_{FS}	105 mm
Θ_{shank}	$[0.3, 71.8, 71.8]^T \cdot 10^3 kg \cdot mm^3$	$lead_{BS}$	2 mm
$l_{beam,Hip}$	1830 mm	$l_{S,0}$	261 mm
$l_{beam,CW}$	1490 mm	$l_S(t)$	221 - 281 mm
m_{beam}	32 073 g	$l_{BS,0}$	191 mm
Θ_{beam}	$[0.14, 69, 69]^T \cdot 10^6 kg \cdot m^3$	$l_{BS}(t)$	116 - 206 mm
h_{beamj}	980 mm	Θ_{LMMA}	$[4.2, 797.2, 799.1]^T \cdot 10^3 kg \cdot m^3$
m_{LMMA}	4542 g	c_{spring}	25 N mm^{-1}
$h_{hipaxis}$	1060 mm		

LMMA is connected to the shank segment through a pin joint fixation, and the back mounting point is connected to the thigh segment. The hip joint is directly mounted on the output shaft of the hip motor (MAXON RE65, #353300 with a gear head MAXON GP81, #110410). In all of the following experiments, we assume that behaviors of this robot are only in a linear vertical hopping space. Namely, the supporting beam of the robot has two degrees of freedom (horizontal and vertical rotations) at the connection to the stand, and the horizontal rotations were set to zero by choosing adequate hip offset angles. With the counterweight, the leg mass (leg mass on the ground) can be adjusted between 0 and 14 kg.

C. Electronics and Control

The electronics of the ETHOP consist of drivers with a power supply for hip, ballscrew, and break motors, sensors, microcontrollers, and a host PC. For the motor drivers, we employed MAXON EPOS2 70/10, which were also used as the interface of analog sensors in the platform. Two rotational potentiometers are installed at the joint of supporting beam, one is installed at the knee joint and a linear potentiometer is installed to measure the spring length during operation. Additional rotational and linear potentiometers are installed on the hip axis and the ballscrew for homing purposes.

The hip and knee actuator are controlled using the "Position-Mode" of the EPOS controllers. The host pc operates information processing and motor command communications through a Matlab interface. The PC sends the position signals with a control frequency of 50 Hz, which results in an acceptable smoothness of movement. The knee actuator has no specific requirements, and any position control strategy can be employed. For the hip control, the behavior of the robot during stance phase highly depends on the control parameters set on the EPOS. During the experiments, we set the parameters as follows: PGain = 300, IGain = 0, DGain = 5000, VelocityFeedForward = 1000, AccelerationFeedForward = 2000.

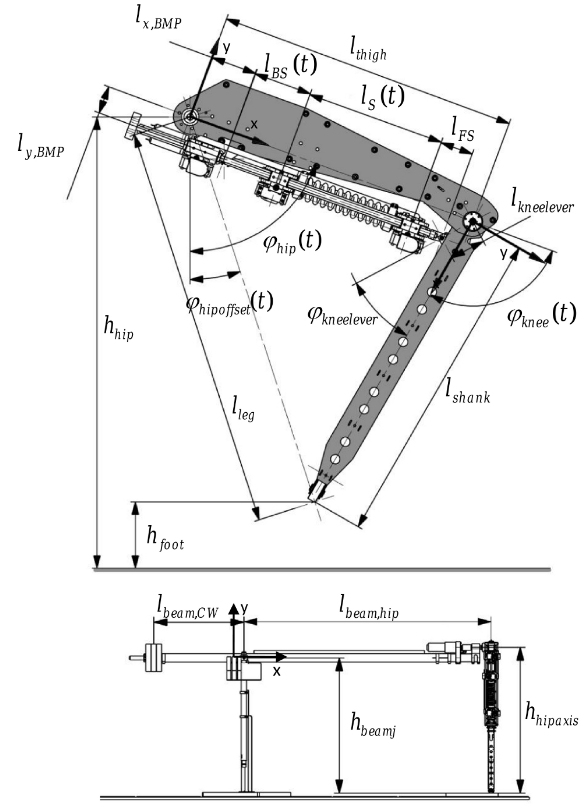

Fig. 3. Parameters of the leg and the beam of the ETHOP.

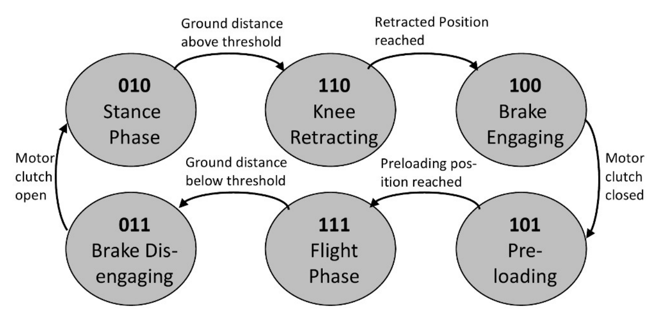

Fig. 4. State machine diagram as we used it for the preloaded hopping experiments.

III. HOPPING CONTROL STRATEGIES

In the rest of this paper, we investigate the vertical hopping induced by two control strategies, i.e. "sinusoidal hopping" and "preloaded hopping". Both hopping strategies consider the actuation in the knee joint, and the hip joint is simply compensate for the leg angle such that the ground contact should be always perpendicular, i.e $\varphi_{hipoffset} = 0°$. This motion is achieved by measuring the knee angle φ_{knee} through the potentiometers in the LMMA, and the changes in this angle are reflected onto the position control of the hip motor by the target angle being $\varphi_{hip} = -\delta\varphi_{knee}$.

A. Sinusoidal Hopping

The sinusoidal hopping is the simplest control strategy in our robotic platform, thus we employ this strategy as

TABLE III
VARIABLES OF THE STATE MACHINE FOR PRELOADED HOPPING

Label	Object	State
0__	Hip height	below threshold
1__	Hip height	above threshold
_0_	Ballscrew	retracted
_1_	Ballscrew	protracted
__0	Motor slide brake	disengaged
__1	Motor slide brake	engaged

the baseline for the systematic analysis of more advanced controllers. In this strategy, the LMMA is set to the series elastic actuation mode (i.e. the front slide brake is engaged), and fixed to the same mode throughout. The ballscrew motor is operated by a PID position controller, in which the host PC send a position signal as:

$$\varphi_{knee} = Asin(\omega t) + B \tag{1}$$

where A, B, ω are amplitude, offset, and frequency parameters, respectively. This controller does not require any global sensory feedback except for the internal position control of the ballscrew and hip motors. Despite its simplicity, this controller usually results in a stable hopping behavior once the parameters in equation 1 are adequately adjusted.

B. Preloaded Hopping

The preloaded hopping is a unique control strategy that requires a legged robot platform equipped with the LMMAs. The basic idea of this controller is to preload the spring of LMMA by using the ballscrew motor during the flight phase, and the stored potential energy in the spring is released during the stance phase. In theory, this strategy should provide a favorable characteristics to legged robot locomotion because the motor in the knee joint can be exploited not only during the stance phase but also in the flight phase, which is usually not the case with the conventional motors.

Practically, this control strategy can be achieved by a simple state machine, which is illustrated in Fig. 4 and 5. The state machine consists of six states that can be represented by the three-bit information shown in Table III, and each bit indicates hip height (measured by the potentiometer on the y-axis of the beam), retract/protract of ballscrew, and engage/disengage of motor side brake, respectively.

The robot always start with "stance phase" (labeled as "010" in Fig. 4) in which the motor side brake should be disengaged. Then, as soon as the leg leaves the ground and the hip height indicates above the threshold, the ballscrew motor controls the knee joint to retract the leg until the knee joint reaches the desired angle (i.e. "110" state). The motor slide brake is then engaged (i.e. "100" state), which bring the state machine to the next state "101". In this state, the ballscrew is extended for preloading the spring, which triggers the state "111". As soon as the hip height passes the threshold again during the flight phase, the motor side brake is disengaged such that the stored potential energy in the spring can be released to the system dynamics. In this state machine, we are able to adjust the following three parameters, i.e. the ballscrew offset position, the spring compression during preloading, and the threshold of hip height.

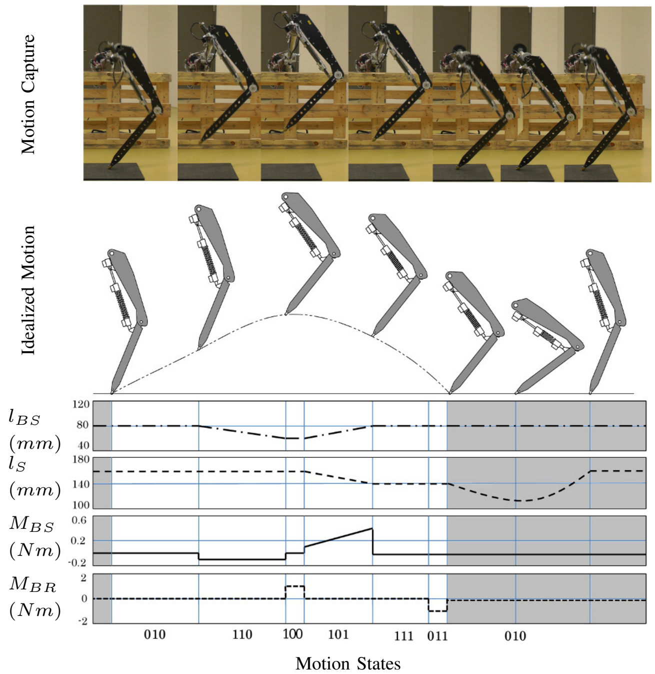

Fig. 5. Preloaded hopping motion pattern. The stance phase is highlighted in grey. The labelling of the motion states follows figure 4 and table III. Below a motion capture series of one hop, the corresponding ballscrew length l_{BS}, spring length l_S, ballscrew motor moment Mt_{BS} and brake motor moment Mt_{Brake} is plotted.

IV. EXPERIMENTS AND ANALYSIS

The two hopping control strategies were implemented and tested in the robotic platform, and we conducted a series of real-world experiments to analyze stability and power consumption of these strategies. This section explains the methods and results.

A. Methods

After a number of preliminary experiments, we identified a set of design parameters that facilitate the analysis of hopping performance. For a fair comparison of two control strategies explained in the previous section, we also tuned the control parameters such that they exhibit a similar hopping trajectory (i.e. the hopping height around 400 mm) regardless of the difference in control strategy. In the sinusoidal hopping controller, we employed a ballscrew initial position of 176.2 mm (which results in an initial knee angle of 72°), a ballscrew amplitude of 16 mm, a ballscrew frequency of 0.34 Hz and a hip offset of $-2°$, with which the ETHOP reaches an average hopping height of 370 mm with 20 hops during the final run. And for the preloaded hopping controller, we set the control parameters as follows: a ballscrew initial position of 186 mm (which results in an initial knee angle of 64°), a spring compression of 24.8 mm, a spring compression speed of 45 mm s^{-1} and a hip offset of $-2°$. With a height threshold of 174 mm the spring is released about 20 mm above the

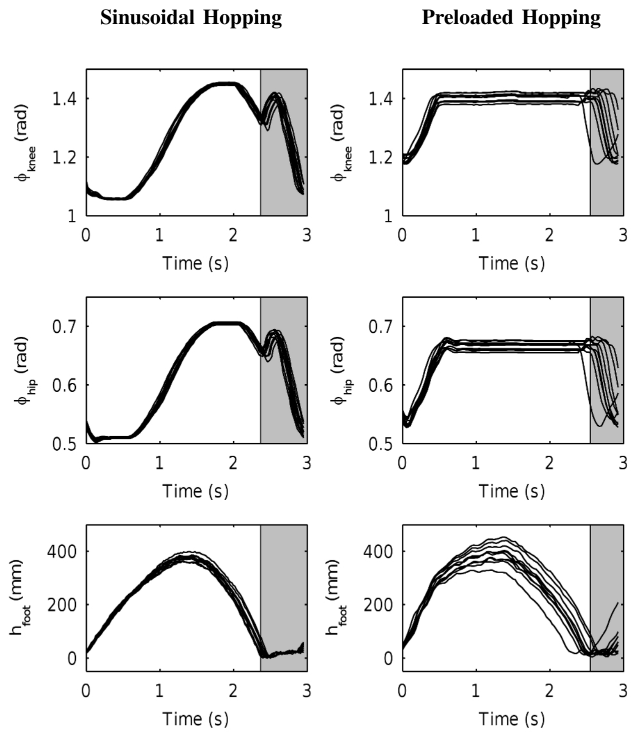

Fig. 6. Trajectory of state variables for one cycle stable behaviour during sinusoidal (left column) and preloaded hopping (right column). The trajectories of ETHOP during 10 consecutive cycles are plotted in one cycle period. The stance phase in each plot is indicated by grey areas.

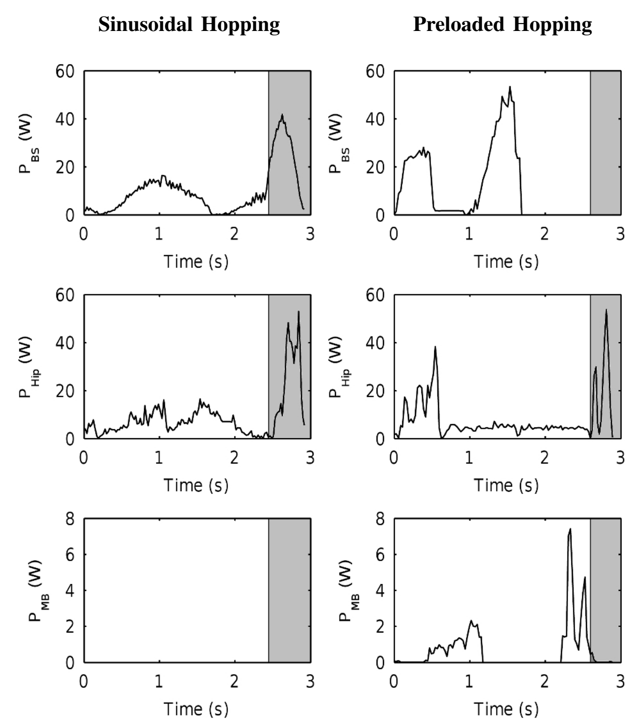

Fig. 7. Power consumption for one cycle stable behaviour during sinusoidal and preloaded hopping. The stance phase in each plot is is indicated by grey areas.

ground. Every joint angle, the ballscrew and spring length as well as the current for hip, ballscrew and brake motor were measured and logged during the run. We performed 20 cycles of hopping experiments in each of the control strategies.

B. Hopping Trajectory and Stability

For each control strategy, we first analyzed the trajectory of stable hopping. In the sinusoidal hopping controller, the hopping height is mainly determined by the amplitude A. For each amplitude between 6 and 20 mm we found an optimal oscillation frequency ω with which the hopping trajectory stabilizes into a steady state after 3-5 hops regardless of the initial hopping height. In contrast, for the preloaded hopping control, the hopping height is mainly determined by the amount of spring compression during the preloading processes.

Fig. 6 shows the trajectories of state variables in both control strategies. Due to the large mass and the low natural frequency of the whole system, both hopping behaviors have long flight phases (ca. 2.5-3.0 sec), and short stance phases (ca. 0.5 sec). The main difference between these two control strategies is most eminently shown in the flight-phase angular trajectories of knee joint φ_{knee}, which are periodic oscillation in the sinusoid hopping controller, whereas it appears to be step function in the preloaded controller. Despite the difference in joint operation, both hopping strategies converge to a similar hopping height approximately at 370 mm.

C. Power Consumption

In order to further characterize the two hopping control strategies, we analyzed the power consumption of hip, ballscrew and brake motors based on the registered data during the experiments. Current and motor speed were measured during the experiments, and the voltage was estimated retroactively by using the motor constants given by the supplier. The input power consumption was calculated as the multiplication of voltage and current, the outcome of ballscrew P_{BS}, hip P_{Hip}, and brake P_{MB} motors for each of the sinusoidal and preloaded hopping controllers is shown in Fig. 7. As expected, there are two significant differences in these two control strategies. On the one hand, we observe energy consumption in the brake motors in the case of preloaded hopping, which do not appear in the sinusoid one; And on the other, the energy consumption of ballscrew motor appears during the flight phase in the preloaded hopping whereas it is in the stance phase for the sinusoidal hopping. The differences in the behaviors of ballscrew motor is mainly originated in the preloading of the spring during the stance phase, while this does not influence the energy consumption in the hip motor.

Fig. 8 shows more comprehensive analysis on the energy expenditure during the stance and flight phases in each of the control strategies. In general, the hip energy consumption is significant, up to 50 percent of the total energy consumption, but even due to a different distribution, the total hip energy consumption per hop is nearly equal for preloaded and

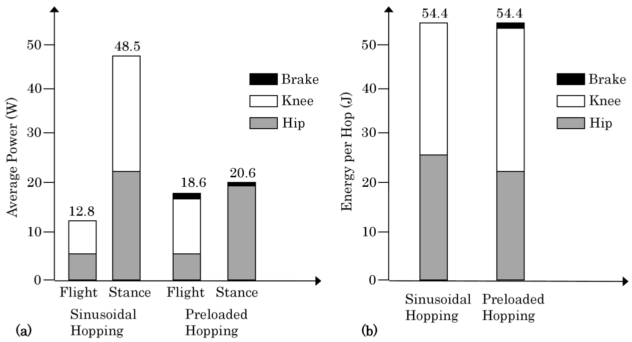

Fig. 8. Power consumption of the two hopping control strategies concerning the average power in flight and stance phase (a) and the total energy per hop (b).

sinusoidal hopping. The clutch energy consumption adds up to only one percent of the ballscrew power consumption. The ballscrew power distribution in flight and stance phase shows a totally different behavior between sinusoidal hopping and preloaded hopping. In preloaded hopping, all the energy is consumed during flight phase, while in sinusoidal hopping the consumption happens mostly during stance phase.

It is important to mention that the use of preloaded hopping strategy can result in two major advantages in the context of hopping robot locomotion. On the one hand, the loading of spring is more efficient and effective during the flight phase than during the stance phase because the peak motor force can be as small as the spring force in the flight phase. And on the other, as long as the flight phase is long enough, the preloading of spring can be achieved almost independently from locomotion dynamics.

V. CONCLUSION

This paper investigated a control strategy of robot hopping based on the newly developed actuator equipped with the small-size discrete couplings. The discrete couplings enables the system to switch between different actuation dynamics, which enrich the variations of control strategies in hopping locomotion. Among others, this paper specifically investigated how to preload the spring during the flight phase such that the motor can efficiently and effectively control the hopping behaviors. By comparing the proposed strategy with a simple hopping control based on an open-loop oscillator, we identified that the preloaded hopping control is able to stabilize the hopping behavior of a one-legged robot, although the energy management can be significantly different. According to our analysis, the proposed control strategy is effective especially in the locomotion with longer flight phase, in which preloading can be achieved more efficiently. In the future, we continue analyzing more comprehensive analysis of energy efficiency in hopping locomotion by exploiting the discrete couplings, including the use of the other operation modes of the LMMA.

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