Neuromuscular reflex based hopping control for a two-segmented robotic leg

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1 Introduction

Human legs are capable of achieving different locomotion tasks (e.g. hopping, walking, running, etc.) with different ground conditions (e.g. flat ground, uneven terrains, soft ground, etc.). Understanding human leg functions are one of the keys to improve the performance of exoskeletons, prosthesis and bipedal robots. It has been shown that compliant leg behavior can explain basic dynamics of hopping, walking and running gaits [1, 2]. Human compliant leg behavior can be generated by neuromuscular properties and neural control circuitries. Simulation studies from [3, 4] have shown that diverse behaviors of human (e.g. dynamic walking and running gait) can be achieved by a neural circuitry that emphasizes spinal feedback. Schumacher and Seyfarth showed that different reflex feedback pathways lead to different behaviors during hopping with a point mass simulation model [5]. However, it remains unclear if this knowledge is applicable to a real robotic system.

Here, we built a hopping robot with a two-segmented leg and implemented the neuromuscular reflex based control for hopping. Different neuromuscular properties and sensorimotor reflexes gains were investigated with a simulation model. By modulating the muscle force reflex feedback gains, we demonstrated that the hopping height can be controlled with a simple reflex based control. Finally, we implemented the controller on the real robot to prove the feasibility of the proposed neuromuscular reflex based control idea.

2 Robot Hardware Design and Simulation

The robot consists of two direct-drive brushless DC (BLDC) motors which control the hip and knee joint separately in the sagittal plane (Figure 1). To minimize the leg moment of inertia, both hip and knee motors are fixed at the top of the thigh. Knee joint is coupled with the knee motor shaft by a rope-pulley mechanism (gear-ratio 4:1). In order to avoid high mechanical stiffness and friction in the transmission chain, no gearbox is used for the motors. The direct drive actuation ensures the transparency between the motor and the external environment [6]. This makes it possible to achieve relative good torque control performance by motor current sensing (without any force/torque sensors).

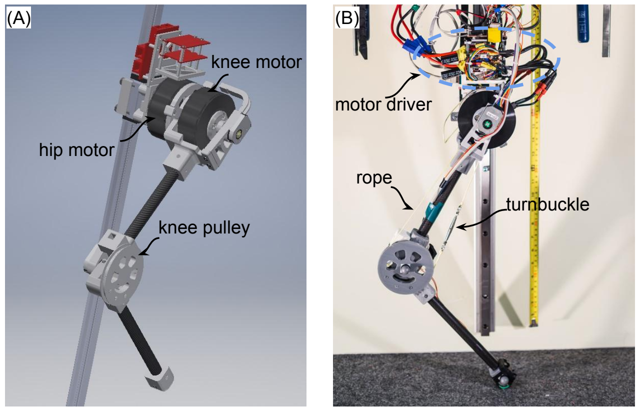

Figure 1: GURO robot. (A) CAD model (without rope and electronic parts). (B) A photo of assembled robot.

Carbon fiber tubes were chosen as the thigh and shank segment to withstand high load while keep the weight an moment of inertia low. All other mechanical parts, except the screws and bearings, are 3D printed with polylactide (PLA) plastic to further reduce the robot weight and keep the cost low. The robot hip is fixed on a 1D linear guide rail so that we can focus on the leg extension function for hopping. The total mass of the robot is 2.8 kg. The thigh and shank segment length is 0.27 m.

Each motor is equipped with a incremental encoder to measure the motor angle. The encoders are used for both low-level current control and high-level reflex based control. A force-sensing resistor is mounted underneath the foot to detect if the robot is in the stance phase or flight phase. An ESP32s microcontroller reads all the sensor data and sends the data to the high-level controller. The high-level control is implemented in realtime at 1 kHz with Matlab Simulink xPC target (Matlab R2018a, Mathworks Inc., USA). The motor drivers and the microcontroller are interfaced with the xPC target machine through EtherCAT communication bus.

A physical simulation model is built in Simscape Multibody (Matlab R2018a, Mathworks Inc., USA) based on the robot CAD design. Each part of the robot is weighed before the assembling. The moment of inertia of every part is calculated based on the measured weight by assuming the density is homogeneous.

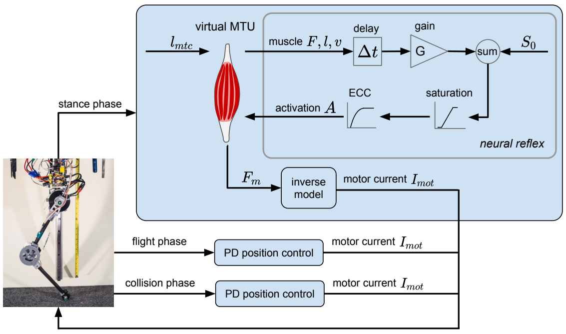

Figure 2: Schematic view of the hopping controller. The force sensor underneath the foot is used to detect if the robot is in stance, flight or collision phase.

3 Neuromuscular reflex based controller

The hopping control are separated into flight, stance, and collision three different phases (shown in Figure 2). During flight phase, both hip and knee joint are position controlled with fixed target angles. The PD values are manually tuned so that the robot can not only achieve the desired posture before next touch down (TD) but also have low effective joint compliance to avoid high impact forces at TD. The collision phase is defined as a short duration time t_c after TD. Both hip and knee motor are position controlled with relatively low P but high D value to absorb the impact energy during the collision. This prevents the shank rebounding if the robot lands on a stiff ground. We set t_c as 20 ms because it is shorter than the human lower limb muscle reflex time while the shank rebound can still be eliminated. The stance phase is defined as the duration between the collision phase and the flight phase. In stance phase, the hip motor is free (desired current 0 A) while the knee motor is controlled to mimic a virtual Hill-type muscle-tendon unit (MTU). The MTU model and muscle excitation-contraction coupling (ECC) model from [3] are used in this paper.

4 Results and discussions

Different sensory feedback pathway (i.e. force, length, velocity) gains were tested. Force and velocity feedback can result in stable hopping patterns (Figure 3). Due to the page limitation, here we only present the return map of hopping height and force feedback gains in Figure 4. Both simulation and hardware experiment results show that higher FFB gain results in higher stable hopping height. The robot hopping height will decrease consistently and eventually stop hopping if the FFB gain is lower than 1.2 in simulation and 1.3 in hardware experiment. The difference between the simulation and hardware experiment results could be due to the estimation of friction and ground contact parameters in the simulation is not closely match the real robot.

5 Conclusions

In this paper, we presented a two-segmented robotic leg and implemented the neuromuscular reflex based control for hopping. The influence of sensorimotor reflex gains to the hopping motion were investigated. We found that stable hopping can be achieved with both positive muscle velocity and force reflex feedback. And the neuromuscular reflex based controller can be implemented on the real robot and generate stable and robust hopping.

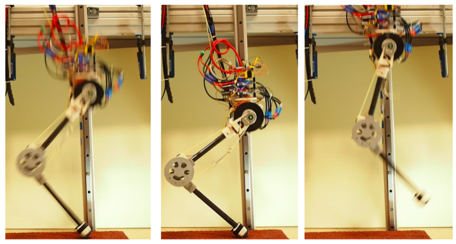

Figure 3: Sanpshots during robot hopping.

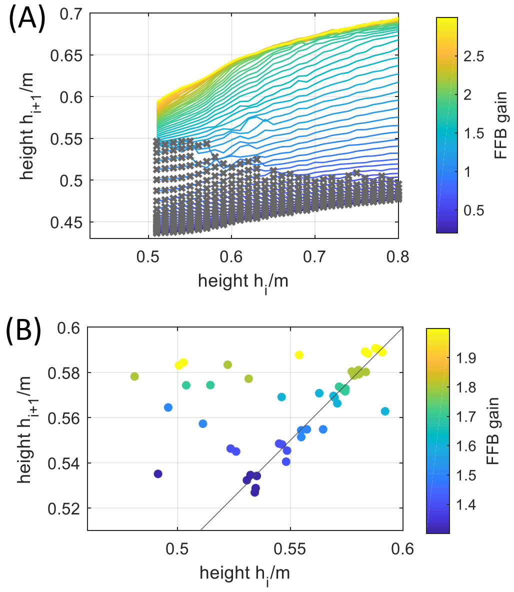

Figure 4: Return map of hopping height and force feedback (FFB) gains in (A) simulation and (B) hardware. Gray cross dots in sub-figure (A) denote the cases which the robot do not rebound.

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