

Effects of Discrete Foot Shape Changes on the Dynamics of a Hopping Robot

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Abstract. Legged locomotion is characterised by a repetitive appearance of impulsive ground collisions which are strongly influencing the locomotion behaviour. The collisions depend on the shape of the contacting foot, but little is known on how the foot needs to be shaped to assist stable and fast locomotion. This paper investigates discrepancies in locomotion dynamics caused by a discrete foot shape change. A curved foot, open-loop controlled hopping robot was built and tested for the experimental investigations which can be switched between two foot shape states. The results indicate that the right timing of foot shape change can induce a variety of locomotion gaits and increased maximal speed, without the shape change doing any work on the robot. Three distinct take off cases were identified which depend on the robot's state and foot shape. The switching between the cases in consecutive hops can explain the observed behaviour qualitatively as presented in this paper.

1 Introduction

In legged locomotion, impacts of a moving body with the ground are well approximated with impulsive forces, especially after McGeer discovered passive dynamic walking in rigid machines [1]. Since then, researchers have found simple models to explain various behaviours in animal locomotion using impact inducing collision models, e.g. in walking [2] or hopping [3]. Impacts are usually considered unavoidable, yet undesirable as they are inherently coupled to mechanical energy loss. Although there are theoretical studies that show cases of legged locomotion without collisional energy loss [4], every legged animal and robot undergoes some loss due to impact in real systems. In fact, it was found that the energetic cost for human like walking is mainly due to the impulsive impacts in the step-to-step transition [5]. Minimising the impact losses can then be achieved by applying toe-off impulses just before the step transition [6], [7]. A detailed collisional analysis of a simple model by Ruina et al. suggests that multiple impacts during the stance phase reduces the energetic loss, due to a sequenced redirection of the centre of mass [8]. Stability considerations in a simple double pendulum model revealed that impacts provide essential stabilising effects which cannot be induced otherwise, e.g. the skipping of unstable portions

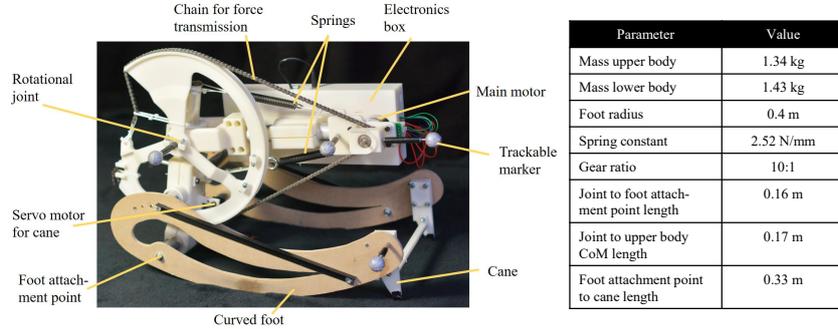


Fig. 1: The robot used to investigate influence of shape changes in hopping on locomotion speed and table with main defining parameter values.

of the phase portrait [9], [10]. Even though mathematical tools exist to analyse the influence of impulsive forces in mechanical systems, e.g. by means of the impulse extended Lyapunov function [11], it is hard to define design rules for legged systems due to the convoluted dependency of dynamics and morphology. Nevertheless, a simple analysis of a bipedal model shows that a flat or round foot shape improves energy efficiency over a point foot model [12], which was also concluded in a study with human subjects [13], where the authors point out that the rolling like behaviour of the centre of pressure progression in human walking is beneficial for the centre of mass redirection in terms of energy efficiency. From this perspective, it is important to carefully design the morphology as a function of impact losses, for which a mathematical method is presented in [14]. Furthermore, it might also be beneficial to change the foot shape during the locomotion gait to adapt to impacts to which the pronation of the human foot just before touchdown might hint [15]. Shape changing locomotive robots have been studied in the past, such as the contour changing wheel [16], yet we had to acknowledge that the role of shape induced impacts in robotics is an understudied topic.

In this paper we are investigating how discrete and controlled shape changes in a hopping robot can alter locomotion properties, and use forward speed as the main measure for comparison. The next section presents the used system and methods to study the influence of shape induced impacts on locomotion, results are illustrated in section 3, section 4 contains an analysis of the main findings, and the last section 5 concludes the paper.

2 Methods

To analyse the influence of shape change during locomotion, a curved foot hopping robot with two linked rigid bodies was built, as is shown in figure 1. This system is driven by a motor torque in the joint between the rigid bodies, generated by a motor on the upper body tip. Two linear extension springs are placed between the upper and lower body to achieve parallel elastic actuation. The robot is equipped with a curved foot shape, which has proven to show good performance in both stability and efficiency [17]. The main geometrical properties of the robot can be found in the table depicted in figure 1. In order to induce a foot shape change during locomotion, a small mechanical structure, from now on referred to as *cane*, is placed in the front tip of the foot which can be either extended or retracted, and hence switch between two discrete shape states. When extended, the front part of the curved foot is bypassed during rolling due to the blocking cane, altering the dynamics and therefore locomotion behaviour. When the cane is retracted the robot moves as if no cane was there to influence locomotion.

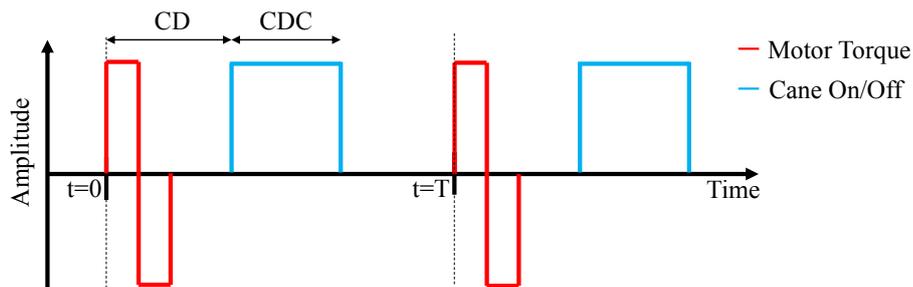


Fig. 2: Main motor and cane open-loop control as a function of time. T is the period of the assigned main motor control frequency, CD is the delay as a fraction of the period, and CDC is the cane duty cycle within the period.

The main motor is controlled by an open-loop signal which induces a motor torque in the robot joint approximated by a bi-directional pulse as shown in figure 2. This type of signal has shown to be better in terms of stability and efficiency as compared to a sinusoidal signal [18]. The motor torque is applied first in positive direction for $100ms$ and then in negative direction for another $100ms$ with respect to the lower body (causing the robot to contract first and then extend) with a torque amplitude of $\pm 0.4Nm$. The period time T is given by the applied control frequency. The cane is being extended according to the cane duty cycle CDC in synchronisation with the motor torque frequency for $CDC \cdot T$ seconds and after a delay of $CD \cdot T$ seconds. The influence of the cane at

various times is tested by varying CDC and CD for constant open-loop control parameters of the motor. It is important to note that the cane is designed not to do any work on the robot when in contact with the ground, but to induce only plastic collisions. The only energy needed to operate the cane is for retraction and extension.

The robot is driven by a 70W Maxon EC 45 flat motor and is controlled via a Roboteq SBL 1360 motor controller. The cane is being retracted with a Parallax 6V standard servo and a linear spring is pulling it back to the extended position if the servo motor is disabled. The robot is untethered and powered by three lithium polymer batteries, providing 24 volts. Radio modules are installed to establish communication with the host pc, and an Arduino Mega 2560 micro controller coordinates the operation. The motion is tracked using 6 reflective markers placed on the robot which are being recorded by an OptiTrack motion capturing system. Trajectories are also being evaluated from video analysis using the software Kinovea.

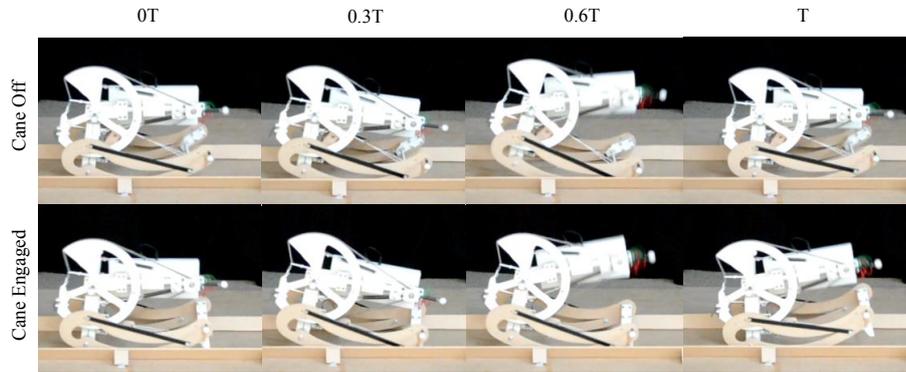


Fig. 3: Robot progression over one period T of the main motor control for the case with retracted cane and extended cane.

3 Results

The following results are shown for a main motor control frequency of $2.8Hz$, and a pulsed motor torque of $\pm 0.4Nm$ for a 10 second run per experiment. It is important to note that the only difference in the remaining report is induced by the timing of the passive cane, not the main motor control.

Figure 4 shows the trajectory of the uppermost tracked marker on the upper body of the robot for different cane control. Figure 4a shows the behaviour with retracted cane throughout the run, and figure 4b the behaviour with permanently

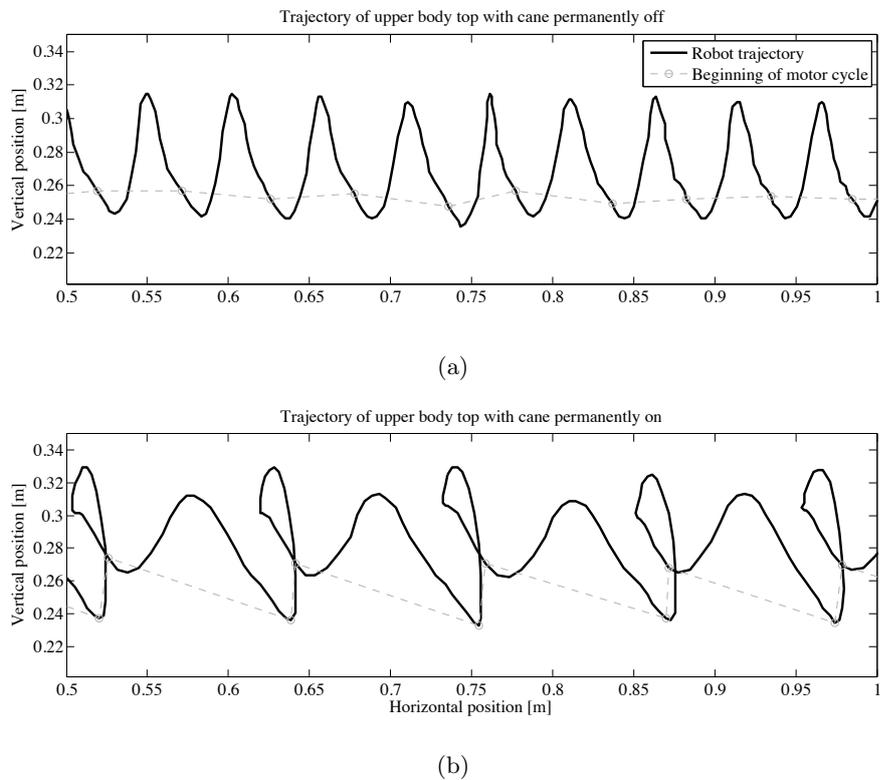


Fig. 4: Trajectories of upper body top marker for a retracted cane (a), and extended cane (b) for the same main motor control. The red circles indicate the main motor timing with period T .

extended cane. The grey circles in both plots indicate the start of a new pulse cycle of the main motor. For the retracted cane case, the dynamics suggest a period-1 behaviour, meaning that the trajectory reaches the initial state after T seconds with respect to the main motor actuation period. For the extended cane, another regular pattern emerges, although the system state returns to identical values only after $2T$. This period-2 behaviour was found to be slightly slower than the cane-less period-1 motion, which might be explained by to the "looping" of the trajectory, i.e. the backward motion of the tracked marker. Figure 5 illustrates the locomotion distance covered as a function of the cane timing. The abscissa shows the cane duty cycle CDC and cane delay per period CD in the format CDC/CD that was applied to the run. A value of $0.5/0.2$ for example indicates a duty cycle of 0.5 and a cane delay of $0.2T$. Figure 5a shows the cane timing for duty cycles of 0.5 and delays between 0 and $0.5T$, whereas figure 5b illustrates cane duty cycles of 1 with delays ranging from 0 to T . The ordinate shows the average travelled distance per hop, which is proportional to

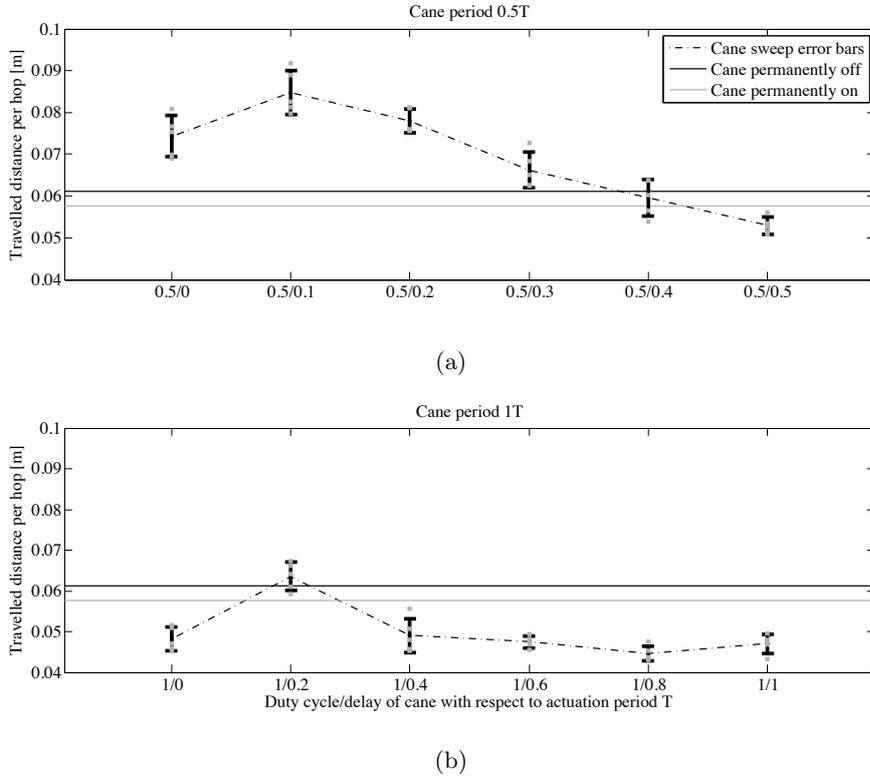


Fig. 5: Averaged travelled distance per hop over a 10s run for different cane timings for open-loop control with $\pm 0.4Nm$ motor torque, and $2.8Hz$ actuation frequency. The cane timing on the abscissa is indicated by cane duty cycle CDC over cane delay per period CD in the format CDC/CD . The error bar indicates one standard deviation for the five sets of experiments that were conducted.

the average hopping speed. The performance of the cane being permanently on or off is indicated with a solid grey or black line, respectively. Note that the robot was initiated from a resting position, and the average hopping distance includes also the initial transient phase. The series of experiments was repeated five times, and the figure shows error bars of one standard deviation around the average.

The results show how for constant main motor control, the travelled distance can be altered significantly by the timing of the cane. If the cane has a duty cycle of 0.5, the hopping distance is increased for almost any cane delay. The peak velocity is reached when the cane is turned on after a delay of $0.1T$, covering a distance of around $8.4cm$ per hop, which is around $\frac{1}{4}$ body length per hop. This corresponds to a speed increase of roughly 40% compared to the cases of the cane being permanently on or off. If the cane is operated only every second

period, which is for duty cycles and delays per period of $CDC + CD \geq 1$, the performance decreases generally compared to the $0.5 CDC$ case and is most of the time even lower than cases of the cane being permanently on or off.

4 Analysis

The apparent increase of hopping speeds as a function of the cane timing may seem surprising given that there is no work being done by the cane, but only passive and energy consuming impacts are induced through the discrete foot shape change. In order to understand what is happening in the collisional process one needs to consider the actual cane contact. Figure 7 shows the trajectory without the initial transient phase of the upper body top marker for the fastest cane control with $CDC 0.5$ and $CD 0.1$ in (b). The parts of the plotted trajectories which are grey indicate contact of the cane with the ground which was extracted visually. It is interesting to note that the "looping" of the upper body trajectory is somehow being avoided by the cane timing of the fast cane control. This is even more surprising, as the motion seems to be rather chaotic and no distinct periodicity can be observed. One might expect the looping to occur at least once, but it was not observed in any of the five trials.

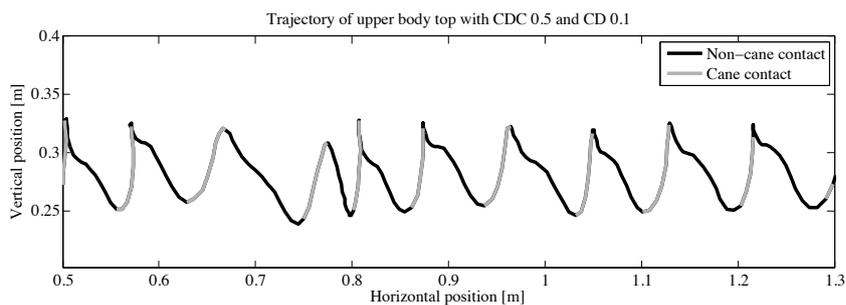


Fig. 6

Fig. 7: Trajectory of the upper body top marker and cane ground contact times for the fastest case with duty cycle of 0.5 and delay of $0.1T$.

After analysing the resulting motion of the robot in the captured trajectories, we identified three occurring cases just before take off which seem to distinctly define the subsequent dynamics. In order to simplify understanding, we are making use of the wheel with eccentric point mass model as is presented in [3] and illustrations of the three cases are depicted in figure 8. The first case (a) is naturally emerging in the stable cane-less hopping motion and is characterised by a leading ground contact point to the centre of mass with respect to the direction of travel just before take off. The impulsive motor torque then causes a

backward rotation during flight phase and the robot lands with a leading centre of mass position relative to the ground contact point. This causes the robot to roll in forward direction after touchdown. Interestingly, the point of touchdown is naturally adjusted such that the same take off posture is achieved after the rolling phase in every hopping iteration, hinting to self-stable characteristics of the system. Case (b) occurs with an extended cane and a forward rolling angular velocity $\dot{\phi}$ which is negligible. The ground contact point and centre of mass of the robot are roughly aligned with respect to the travelling direction. The take off impulse causes a strong backward rotation, shifting the point of touchdown further back than in case (a) and hence inducing accelerated rolling in the next hopping iteration. Lastly, case (c) is observed with an extended cane and a forward rolling angular velocity $\dot{\phi} \gg 0$. In this case, the impulsive impact of the cane with the ground induces a rotation of the centre of mass around the point of cane contact, which promotes a ballistic trajectory that is favourable for a long jump. This behaviour is similar to pole vaulting, where the athlete is using the pole's contact point as a centre of rotation to surpass a raised bar. Due to the ballistic effect, the pulsed actuation torque can only cause a slight backward rotation, leading to a small distance of point of touchdown and centre of mass in travelling direction. This means that the gained rolling speed during stance phase is the smallest of the three presented cases.

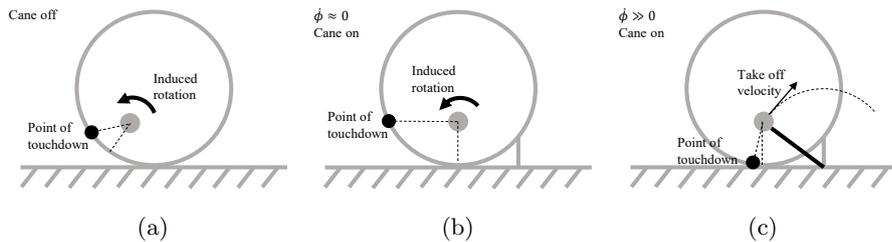


Fig. 8: Three cases of observed take off positions using a wheel with eccentric point mass model presented in [3]. The grey filled circles indicate the centre of mass of the robot model, and the black arrows show the main take off motion after the pulsed motor torque was applied.

The three shown cases can be used to explain the observed discrepancies in locomotion trajectories. As was already explained, case (a) causes the cane-less period-1 motion, which naturally emerges after a few transient hops. The period-2 motion, as shown for example in figure 7(a) with the cane being permanently engaged, is explained by a switching between cases (b) and (c). The high rolling velocity $\dot{\phi} \gg 0$ in case (b) after touchdown causes the pole vaulting effect seen in case (c), and the small rotational retraction in case (c) then causes a small angular rolling velocity $\dot{\phi} \approx 0$, which in turn gives rise to case (b) in the next hopping iteration. Now, how can this simple model explain the trajectories observed in 7(b) for the $CDC/CD = 0.5/0.1$? We observed that this cane control

causes the robot to operate mostly in case (c), the pole vaulting mode. Whenever the decelerating case (b) is about to be induced by a previous case (c), the cane is being blocked by the ground and can not extend due to the body posture and previous retraction of cane, which really induces the faster cane-less case (a) instead of (b). The robot naturally chooses the best option for increased locomotion speed with this control and avoids case (b) completely, only operating in (c) and switching to (a) in some extreme cases. Figure 9 compares the transient phase of the best control case $CDC/CD = 0.5/0.1$ and the case with permanently engaged cane. The first appearance of the blocking cane, inducing the state (a) instead of (b) and avoiding the decelerating looping trajectory, is indicated as well.

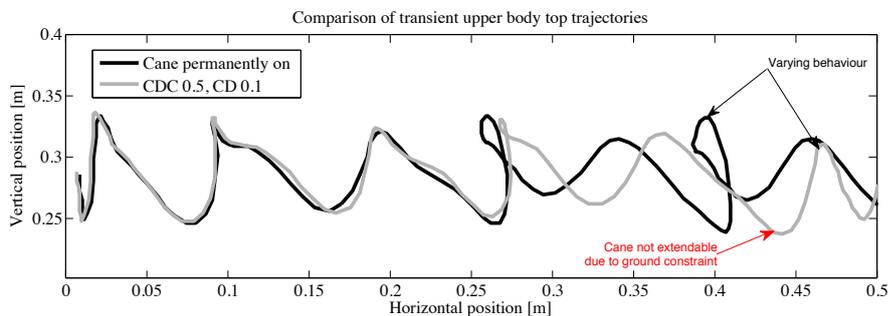


Fig. 9: Transient trajectories of the upper body top marker for the case with the cane being permanently on, and the case with duty cycle of 0.5 and delay of $0.1T$.

5 Conclusion

In this paper we presented that a discrete change in foot shape during locomotion of an open-loop controlled hopping robot can induce a variety of locomotion gaits and increase the travelling speed. The foot shape is passive and does not do any work on the robot, but influences the time and direction of dissipative impacts. With a simple model, three distinct cases were identified just before take off, which define how the pulsed torque influences the touchdown posture. The fastest locomotion speed can only be achieved by switching between the accelerating cases and avoiding the decelerating case, which can be achieved by the right timing of shape change. The presented insights may provide a new perspective for the development of control laws for increased locomotion stability, efficiency and speed through foot shape changes.

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