Effects of Compliant Ankles on Gait Characteristics of Flat-Feet Limit-Cycle Walkers

Mansoor Alghooneh[1] and Christine Q. Wu[2]

1- Background and Significance

Limit-cycle walkers are capable of exhibiting high energy-efficient and natural gait [1]. However, they are mostly of point or round feet, which are not capable of achieving safe standing and experiencing foot strike. Furthermore, their step length and walking velocity are fixed for a determined set of actuation, mass, and geometrical parameters since they own a fixed walking gait sequence i.e. single support and single impact.

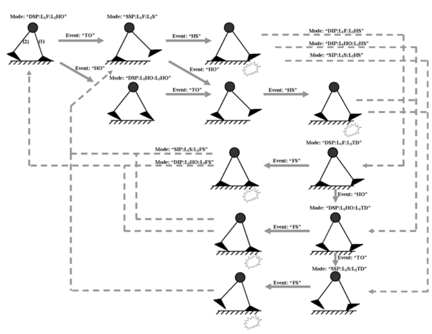


Fig. 1. Flat-feet limit-cycle walkers possess multiple walking sequences due to unilateral constraints of the feet with the ground.

To solve the aforementioned limitations, flat feet are incorporated to limit-cycle walkers via compliant ankles. Therefore, these walkers can realize safe standing and foot strike. More importantly, they exhibit variable step length and walking velocity for a determined set of actuation, mass, and geometrical parameters because of multiple walking sequences due to unilateral constraints of the feet with the ground, shown in Fig. 1. However, despite advantages of flat feet, they bring up complicated challenges, among which walking gait is now a non-predefined sequence selected among twelve gait postures and four gait events, referred to Fig. 1, which can be categorized into single support, double support, single impact and double impact.

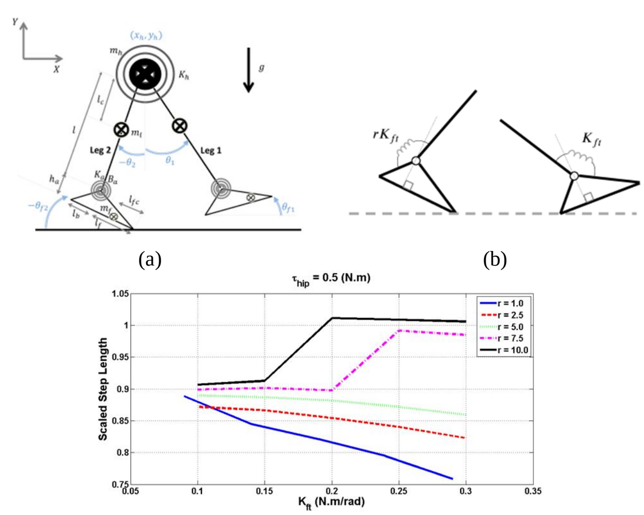
The significant goal of this research is to explore the effects of compliant ankles on gait characteristics of flat-feet limit-cycle walkers e.g. step length and step velocity. More specifically, it is to answer whether adjusting ankle compliance is an effective approach to control the step length and walking velocity.

2- Methodologies

The simplest flat-feet limit-cycle walker of Fig.2a is equipped with compliant ankles, actuated by a constant hip torque only during the single support phase to compensate energy loss at heel and foot strikes, and ankle damping to be capable of walking on the level ground. The impedance of the feet is adjusted by springs with piecewise rotational stiffness that contain the front-side and back-side, shown in Fig. 2b. When the angle between the forefoot and the leg is more than 90^o, the front-side ankle stiffness is in effect, and when the angle is less than or equal to 90^o, the back-side stiffness is active. Accordingly, the piecewise stiffness at the ankles is addressed by the front-side ankle stiffness K_{ft} and the ankle stiffness ratio r which is the ratio of back-side and front-side stiffness. A comprehensive computer program has been developed to extract the limit-cycle gait from all gait sequences of Fig. 1 by interconnecting the Poincare mapping and the Newton-Raphson method.

3- Results and Conclusions

This research promises high potential of exploring different strategies for adjusting the compliant ankles *(a)* to control the step length and walking velocity of flat-feet limit-cycle walkers, and *(b)* to control the impedance of active prosthesis feet. As a result, referred to Fig. 2c, this research concludes that when the piecewise rotational ankle stiffness increases under a specific level of the ankle stiffness ratio, the step length and walking velocity decrease but the step period increases. Furthermore, premature heel off, occurring for a certain range of ankle stiffness at the trailing foot during single support phase, makes a dramatic increase in the step length and walking velocity, but does not influence the step period.



(a) (b) (c)

Fig. 2. (a) Schematic of the limit-cycle flat-feet walker; (b) Schematic of piecewise torsional stiffness at the ankles; (c) Step length versus the front-side ankle stiffness K_{ft} for different ankle stiffness ratio r.

References

[1] S. H. Collins et al., *International Journal of Robotics Research*, vol. 20, pp. 607-615, 2001.

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Does Premature Heel-Off improve Energetics of Flat-Feet Limit-Cycle Walkers?

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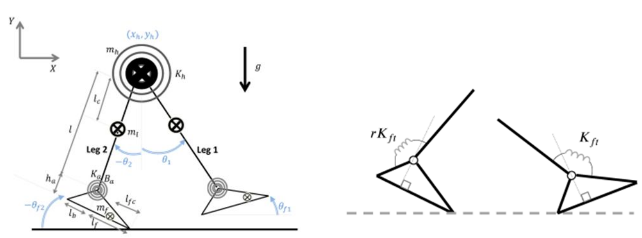
1- Background and Significance

Limit-cycle walkers that splendidly adapt to their natural dynamics possess high energy-efficient and natural gait. However, since these walkers are mostly of point or round feet [1], they are deprived of experiencing premature heel-off, which is a significant event occurring when the heel of the trailing foot lifts from the ground during the single support phase of bipedal walking [1]. To solve the aforementioned limitations, flat feet have recently been incorporated to limit-cycle walkers via compliant ankles [1, 2].

Despite the fact that premature heel-off dramatically influences step length, walking velocity, and energetics in limit-cycle bipedal walking, it has rarely been studied [1]. Therefore, this research is to explore how premature heel-off influences energetics of limit-cycle walkers i.e. active mechanical energy consumption and active cost of transport.

2- Methodologies

The simplest flat-feet limit-cycle walker of Fig.1a is equipped with compliant ankles, actuated by a constant hip torque only during the single support phase to compensate energy loss at heel and foot strikes, and ankle damping to be capable of walking on the level ground. The impedance of the feet is adjusted by springs with piecewise rotational stiffness that contain the front-side and back-side, shown in Fig. 1b. When the angle between the forefoot and the leg is more than 90^{o}, the front-side ankle stiffness is in effect, and when the angle is less than or equal to 90^{o}, the back-side stiffness is active. Accordingly, the piecewise stiffness at the ankles is addressed by the front-side ankle stiffness K_{ft} and the ankle stiffness ratio r which is the ratio of back-side and front-side stiffness. A comprehensive computer program has been developed to extract the limit-cycle gait by interconnecting the Poincare mapping and the Newton-Raphson method.



(a) (b)

Fig. 1. (a) Schematic of the limit-cycle flat-feet walker; (b) Schematic of piecewise torsional stiffness at the ankles.

3- Results and Conclusions

Fig. 2 shows ascending trend in the step length and walking velocity at a specific range of ankle stiffness due to premature heel-off. Fig. 3a shows that the active mechanical energy consumption [energy injected by the hip actuation] increases when premature heel-off occurs, but Fig. 3b evidences descending trend in the active cost of transport [active mechanical energy per travelled distance per walker's weight] when premature heel-off occurs due to the fact that the cost depends on both the active energy consumption and the step length. Finally, this research work concludes that premature heel-off significantly improves the active cost of transport, but increases the active energy consumption of limit-cycle walkers.

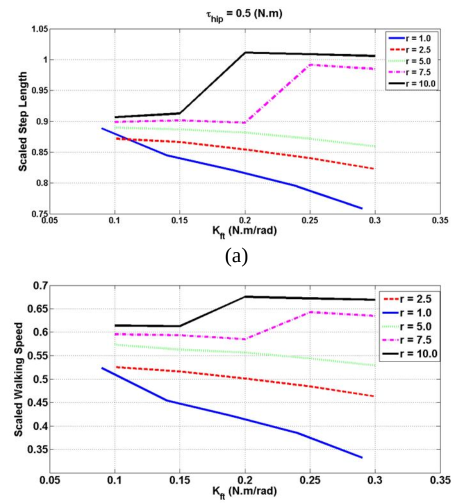


Fig. 2. (a) and (b) represent the step length and the walking velocity versus the front-side ankle stiffness K_{ft} for different ankle stiffness ratio r.

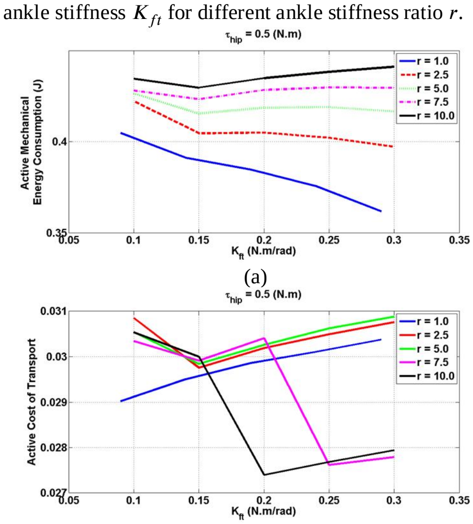


Fig. 3. (a) and (b) represent the active mechanical energy consumption and the active cost of transport versus the front-side ankle stiffness K_{ft} for different ankle stiffness ratio r, respectively.

References

[1] D. G. E. Hobbelen et al. *International Journal of Robotics Research* vol. 27, pp. 709-735, 2008.

[2] M. Alghooneh and C. Q. Wu, "Effects of Compliant Ankles on Gait Characteristics of Flat-Feet Limit-Cycle Walkers," presented at the Dynamic Walking, 2013.

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