The role of foot-ground interaction and slip during bipedal walking on granular media

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Bipedal walking of humans and robots is well studied on ground where feet neither slip nor penetrate the substrate [1, 2, 3, 4]. In such situations, walking is characterized by a swing phase (during which one foot is lifted and the other is planted on the ground) and a double support phase (during which both feet are in contact with the ground). Ground reaction forces during the double support phase are dependent on the ground interaction of each foot; small differences between the ground interactions of each of the feet can generate complex slipping patterns or 3-D torques which can result in rotations in the yaw, pitch, and roll of the lomotor [5, 6]. To avoid modeling such complexity many models of bipedal walking approximate the double support phase as instantaneous [7, 8].

When walking through flowable media like sand or snow however, a finite duration double phase must occur: of interest to us are such interactions that occur during the foot (and lower limb) intrusion and extrusion phases. During such phases, motion of the two feet relative to each other and the resultant drag forces on each foot will determine if a foot slips in the material, thus degrading the kinematic and energetic performance of the walker. To examine these issues, we study the locomotion of a planarized bipedal walking robot (1.6 kg, 40 cm tall) which can translate only in the vertical and fore-aft directions. The 8 motor robot (4 per limb) walks on a fluidized bed of poppy seeds at different granular compactions. The motors are controlled to generate gaits with varying foot insertion trajectories. Our scheme used an open loop control that precomputes angular positions for each motor as a function of time.

Our robot walked successfully for most parameters other than loose compactions and high angles of foot intrusion (above 30 degree presentation angle). However, we noticed an asymmetry between each step in the gait: one leg made consistently shorter strides than the other by up to 25 percent and differences in standing leg height by up to 0.5 percent. We discovered that this difference in stride length and leg height resulted from deviations within 5 degrees in the model for the commanded and actual position of each motor; the sum of these slight deviations resulted in a noticeable effect over the four links. While unintentional, this gait allowed us to explore the differential slipping that can occur during the traditional double support phase in granular media. During this phase, when there is motion between the two feet relative to each other (as would occur in an asymmetric gait), only one foot will slip while the foot lower in the ground will remain planted because objects deeper in granular media experience proportionally higher drag forces. We define this slip as the "double support slip."

To better understand and control slipping during locomotion on granular media, we modeled the robot in the Chrono simulation engine [9] and used experimentally validated Resistive Force Theory [10] to calculate the granular ground reaction forces on the feet and lower limbs. Even without inputting an asymmetry between the two steps, the simulated robot experienced slip during the intrusion phase in the granular media. The amount of slip depended on the foot presentation angle. We define this slip as the intrusion slip. When adding the intrusion slip measured from simulation to the double support slip measured experimentally, we modeled the total slip that the asymmetrically stepping experimental robot experienced while walking over granular media. We conclude that the dynamics of bipedal walking over granular media can be strongly affected by differential slipping experienced during the two-foot interaction with the material.

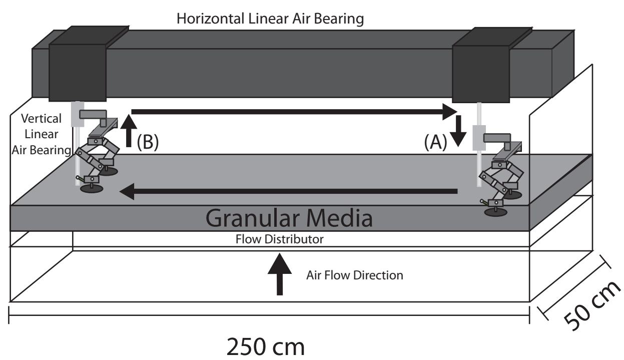

Figure 1: An automated granular bipedal walking apparatus. The robot is planarized by vertical and horizontal linear air beaings, allowing fore-aft and vertical motion. The robot is lowered onto the bed of granular media (A) and allowed to walk with a gait of a particular presentation angle (the highest angle at which the foot reaches while penetrating into the material). When the robot reaches the end of the trackway (B), it is lifted and pulled back to the start while air is run through the poppy seeds, resetting the material into a new, uniform state of desired volume fraction.

References

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