Passive mechanical stabilization of body rotations in jumping

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Summary

Jumping is an important mode of locomotion, and also used to capture prey or avoid predators by many terrestrial animals. However, in their natural habitats, most animals typically push off against muddy and unpredictable terrains, inducing the feet to apply unequal forces on the ground. This will often result in substantial yawing angular momentum at take-off, and have dire consequences such as the animal's mouth pointing away from an intended prey, or landing in ways that prevent escaping a predator. We investigated whether the passive mechanical response of the body could aid stability. We used a mechanical jumper and examined its yaw dynamics in the frontal plane as it pushed off unequally using two legs. Here, we report a previously unknown function of the pelvis in stabilizing yaw at take-off. We find that the passive mechanics involving a flexible pelvis nearly completely eliminates the angular momentum at takeoff. The primary mechanism is that a flexible pelvis keeps the weaker foot in contact for a longer duration, thus applying a balancing impulse. Our discovery of stability in these jumpers suggest designs for robotic jumpers and point to the critical role of pelvis morphology in jumping animals.

1 Introduction

Many terrestrial animals lack aerodynamic devices such as wings or large webbed feet to exert control over their angular momentum once airborne. One approach that is employed by animals such as geckos and lizards is to use their tail as an inertial rotor in order to reorient their body [1]. These are zero-angular momentum maneuvers that involve a combination of the tail and spine [2], and use sensory neural feedback control during the airborne phase.

Unlike lizards or geckos, many adept jumpers rely on ballistic jumps for catching prey or avoiding predators, and do not modulate their angular momentum after take-off. Frogs routinely leap out of the water in ballistic jumps to catch prey. Occasionally they miss the prey, thus illustrating the open-loop nature of these jumps (`https://bit.ly/2Uv2Iys`). Similarly, locusts are adept at achieving nearly zero yaw angular momentum at take-off [3, 4] even if suddenly modifying their direction at take-off [3]. Some animals have evolved elaborate gear-like structures to eliminate kinematic asymmetries between their legs [5], but kinematic symmetry does not imply equal forces. The mechanism of yaw stability in these animals remains unknown.

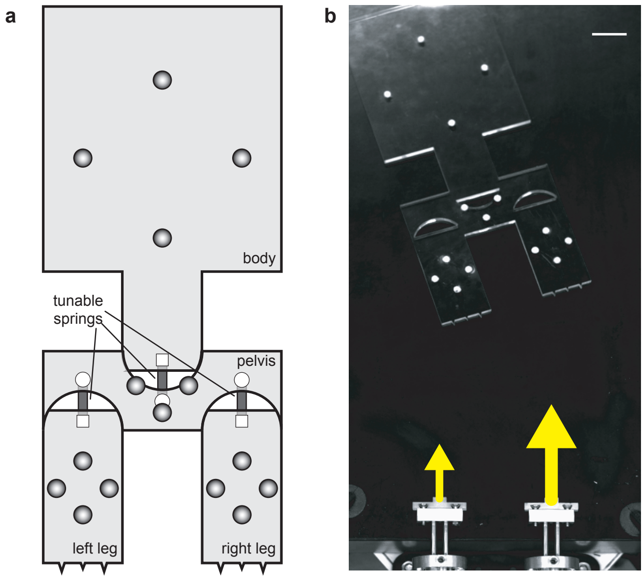

Figure 1: Mechanical jumper in the frontal plane. **a,** The jumper has a body, pelvis and two legs. The three joints have a tunable stiffness that is modulated by changing the pre-stress of an elastomer that spans the joint. Reflective markers and high-speed video track the jumper's kinematics. **b,** A rigid jumper that is propelled by unequal forces on the two legs, using pneumatic motors attached to the ground, takes-off with yaw angular momentum.

Yaw, the rotation seen in the frontal plane (fig. 1), is the chief angular momentum component for many jumping animals that push-off using more than one foot. This is because the points of application of force are medio-laterally separated. Also, the use of multiple feet often simplifies to two feet because most animals rely on their hind legs for propulsion during jumping [3, 6]. Force imbalances arise because of intrinsic asymmetries between the feet, the nature of the substrate against which they push, and because of the desire to jump in directions away from their initial heading.

Even if the two feet apply unequal forces on the ground, the angular momentum may be small under certain circumstances. The angular momentum induced by the normal forces may be negated by either the weaker leg staying in contact for an appropriately longer duration, thus applying the same impulse as the stronger leg. Additionally, the legs could apply a net shear force (if friction permits), to cause the net force vector to pass through the center of mass. We investigate both these routes to stability.

2 Methods

Tests were performed with mechanical jumpers on an inclined air table (5°) (fig. 1). Two pneumatic motors pushed up on the two legs. The air intake to the left motor was partially choked to make that the weaker leg. Motion capture cameras (Vicon Inc.) and high speed video (Photron Inc.) were used to track the different rigid segments of the jumper.

We used 3 pelvis stiffnesses: *rigid* and two flexible—*stiff* and *soft*. The rigid pelvis was fabricated as a monolithic piece. Stiffness was modulated for the other two using an elastomer that spanned the joint and whose tension could be preset using graduated markings. The softest jumper had joint stiffnesses that barely stabilized it against self-weight. The stiff (and flexible) jumper had a consistently maintained higher stiffness than the softest. We tested 4 foot designs to assess the effect of shear forces or varying center-of-pressure under the foot: point contact (x), distributed contact that supports moments (m), a notched contact that supports shear (s) and a distributed, notched contact that supports both shear and moments (sm). The experiments were repeated with 4 different line pressures and we performed 3 repetitions for every parameter combination. Total angular momentum, and not just the body's, was used in analyses.

3 Results

A flexible pelvis nearly completely eliminates the angular momentum (fig. 2a–c). Having the ability to exert shear forces or moments with the foot also help (feet: `s`, `m`, and `sm` versus `x`). But, the effect of the foot is trivial compared to the 100–1000 fold reduction in angular momentum due to a flexible pelvis. If the joints are too soft, with stiffness barely able to prevent buckling under self-weight, then the angular momentum at take-off is a little worse than the slightly stiffer, yet flexible, pelvis. The underlying reason for the stabilizing influence of the flexible pelvis is that the flexibility causes the weaker foot to stay in contact for a longer duration with the ground than the stronger foot (fig. 2d).

4 Discussion

The stiffness of the pelvis was selected to be sufficiently stiff to prevent buckling, but not tuned for each of the 4 different line-pressures, i.e. 4 different jumping intensities. This demonstrates the robustness of pelvis flexibility as a strategy. Importantly, the pelvis stiffness in animals could be actively controlled through muscular contraction. Our works shows how the mechanical design of the pelvis may have played a central role in the evolution of jumping as a viable mode of locomotion and survival. Finally, our work suggests simple design modifications to existing agile robots to improve their stability in jumping.

5 Acknowledgement

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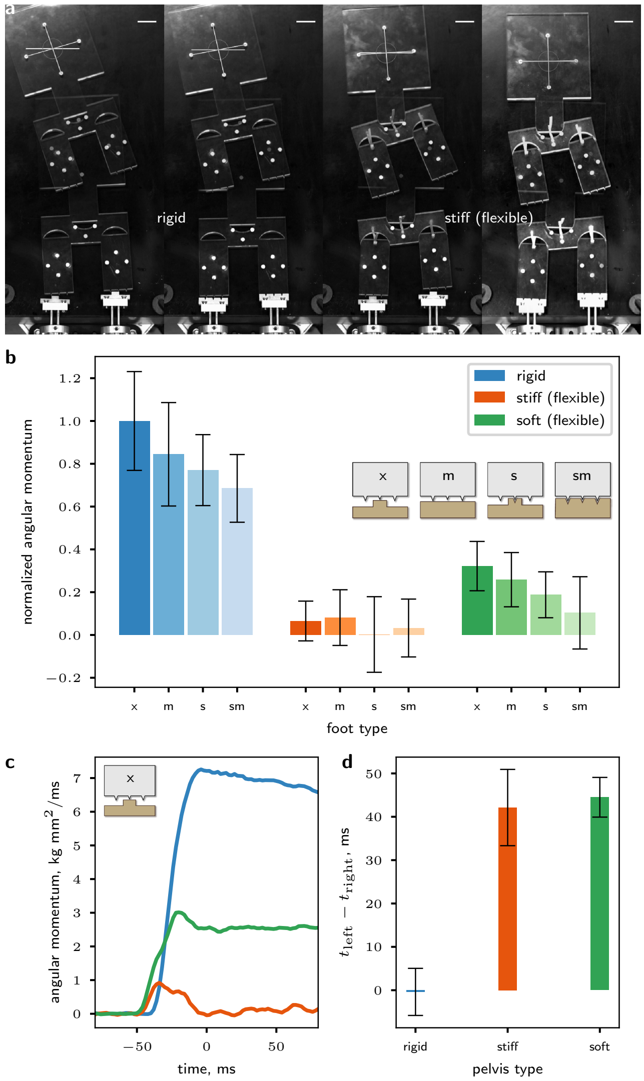

Figure 2: Effect of pelvis flexibility and foot morphology. **a–c,** Angular momentum at take-off is nearly nullified by a flexible pelvis. But, if the pelvis is too soft (**b**), buckling instabilities partly counteract the stabilizing influence. **d**, Pelvis flexibility causes the weaker foot (left) to stay in ground contact for longer than the stronger foot (right). This stabilizes the angular momentum (**c**) before take-off at 0 ms.

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