HOP, SKIP, AND A JUMP: INVESTIGATING WHY PEOPLE JUMP IN RESPONSE TO WALKING PERTURBATIONS

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Introduction: What causes people to fall in the real world? Despite a vast amount of literature investigating balance metrics in response to perturbations, it may be the strategy that is required for balance recovery that causes people to fall rather than the magnitude of imbalance itself. In our recent work, we studied the balance and recovery strategies used to respond to perturbations that varied in magnitude, direction, and timing [1]. As a result of studying a thorough sweep of these variables (96 conditions), we observed a niche set of conditions that elicited an extreme balance recovery strategy; in over 20% of responses to some conditions, individuals jumped. Here, we took a closer look at the jump responses in our data set by analyzing two situations that we hypothesized would elicit a jump response and the three jump mechanisms that we observed.

Methods: We used our previously published data set; 11 participants walked while being exposed to ground perturbations that varied in magnitude, direction, and timing [1]. We hypothesized that **H1)** participants jumped to avoid a **collision** of the swing limb with the stance limb, typically elicited during a crossover step (Fig. 1A). We quantified this using the velocity vectors of the swing foot in the 150 ms leading to the jump; we classified a projected collision if the velocity vector of any swing foot marker was projected to collide with the region defined by the stance foot markers. If this was not the case, we hypothesized that **H2)** remaining jumps occurred if the required step width was **too narrow** and fell outside the capabilities of the participant (Fig. 1B). To quantify this, we fit a participant-specific center of mass-driven model [2] to the four steps after each non-jump perturbation trial. We used this model and center of mass mechanics leading up to the jump to project the required step width had the participant not jumped. We quantified three mechanisms that individuals use to jump (Fig. 1C); 1) a lateral **skip** strategy involves pushing off of the stance foot and landing on that same foot lateral to the original position, 2) a **foot replacement** strategy involves hopping into the air with the stance foot and landing in the same location with your swing foot, and 3) a **leap** strategy involves hopping into the air with the stance foot and landing anteriorly with the swing foot.

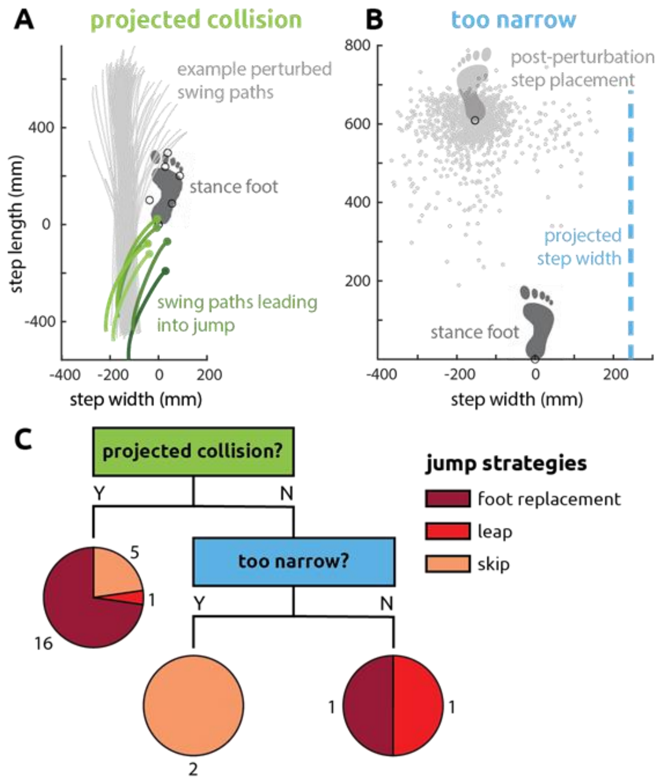

Figure 1: (A) Lines show swing foot heel marker relative to stance foot; grey lines are non-jump responses, green lines are swing phase leading up to jump. **(B)** Grey dots show non-jump post-perturbation steps, blue line shows a trial's projected step width from the linear model, which is a narrower step than any successfully executed step by the participant. **(C)** Decision tree showing the jump strategies used in response to projected collisions and too narrow steps.

Results & Discussion: Of the 26 trials with jump responses analyzed from the data set, 22 trials were projected to have a limb collision. In the jumps that followed the projected limb collision, 16/22 used a foot replacement strategy, 5/22 used a skip strategy, and 1/22 used a leap strategy. In the remaining 4 trials that did not include a projected limb collision, 2/4 were projected to require too narrow of a step. In both of these trials, individuals used a skip strategy. In the remaining 2 trials that did not present a collision or too narrow of a step, the foot replacement and leap strategies were both used once. Broadly, this work identifies potential limb collisions during a narrowing step maneuver as the leading cause of jump responses following perturbations. In these situations, participants dominantly reacted by using a foot replacement strategy; in addition to preventing a collision, this strategy effectively turns a narrowing step into a widening step, which may set up the participant to a wider range of maneuvers on the subsequent step. The lateral skip strategy effectively does the same, which is executed for the remaining steps that are too narrow.

Significance: Here, we identified some of the more demanding balance recovery mechanisms that have been reported, with only two other studies that we are aware of reporting jump responses [3,4]. The perturbation conditions that caused jumps could be a useful tool to study highly destabilizing scenarios, especially those that may cause a fall in balance-impaired individuals. These responses are also important to consider in the development of wearable robots, as these strategies may present edge cases for existing control architectures. Lastly, these responses pose an interesting stance/swing limb constraint challenge that should also be considered in bipedal robotics.

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References: [1] Leestma et al. (2023), *J Exp Biol* [2] Joshi, Srinivasan (2019), *J R Soc Interface* [3] Eveld et al. (2020), *Mid-South Biomechanics Conference* [4] Pijnappels et al. (2004), *J Biomech*