Balancing on Slacklines: Modeling and Empirical Evaluation

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I. Motivation

The way how humans maintain balance during standing and locomotion has been an active area of research for many years now, with applications in bipedal robotics, leg prosthetics, and rehabilitation. However, most studies are limited to standing and walking on immobile surfaces, or on externally perturbed platforms and treadmills. Less is known about unstable, passive support surfaces that move in interaction with the human standing on it, such as suspended platforms, tightropes, or slacklines. Slacklining (balancing on a slack rope) is a young sport that became popular in the climbing community and is now reaching a broader public. It has shown positive training effects on balance, as well as related reflex adaptation [1] and changes in strength [2]. However, neuromechanical control strategies during slacklining remain unclear.

II. State of the Art

As balancing on a slackline is hardest in medio-lateral direction, the task has mostly been analyzed in the frontal plane only. Then, the two fixed points of the line both project onto a single point, called the "anchor point" (AP) in the following. For static equilibrium, the AP, the human's center of mass (CoM), and the contact point between stance foot and line have to be aligned in vertical direction [3].

On rigid surfaces, humans control balance during standing and walking by a set of strategies, depending on the perturbation [4]–[6]: The "ankle strategy" moves the center of pressure (CoP), the "hip strategy" moves the upper body in the opposite direction with respect to the lower body, "windmilling" the arms changes the body's angular momentum, and foot placement modifies the base of support (BoS).

On a slackline, only a subset of these strategies can be used in medio-lateral direction: The BoS is negligibly small and cannot be extended, and the CoP is coupled to the location of the slackline. As expected from these constraints, kinematic data reveals that the arms play an important role in the task [3].

A first dynamic model [7] describes the constraints imposed on the foot by the slackline as a cart on a circular path, while the movement of the entire body is reduced to an inverted pendulum with an external control moment acting on it. The control task is solved via optimal control. One limitation of this model is that it does not provide insights into the interplay of segments, in particular the distribution of tasks between legs, trunk, and arms. Furthermore, its predictions have not been compared to physiological movements.

III. Own Approach

Here, we model single-leg stance on a slackline with a focus on the distribution of control tasks between stance leg, arms, and residual body. In line with previous theories, we assume that humans aim to minimize energy consumption and to maximize stability margin.

A major challenge in slacklining is that it is not possible to influence the line of action of the slackline reaction force without moving the leg. The line of action always passes through the subject's foot and the AP. Therefore, in contrast to rigid surfaces [8], there are severe constraints for possible control strategies. However, within these limitations, it is still possible to influence the horizontal force components that act on the body. We hypothesize that this possibility is exploited by decoupling the movement of the stance leg from the upper body (by means of low co-contraction levels in the hip), and by dynamically using the stance leg to direct the force vector. Further, the model predicts that the arms play a dominant role in controlling angular momentum.

We compared model predictions with experimental data from 16 slackliners of different skill level. From recorded kinematics and kinetics of single-leg stance, we calculated measures for energy consumption, stability, and leg decoupling, and we tested for correlations with skill level.

IV. Current Results

The experimental results are at least partially in line with the model predictions: More skilled slackliners consume significantly less energy ($p < 0.001$), and they show a tendency to increasingly decouple the stance leg from the residual body ($p < 0.1$). However, we found no clear evidence for the arms as the dominant control mechanism for angular momentum.

V. Best Possible Outcome

We anticipate that analysis of challenging tasks such as slacklining will provide new insights into neuromechanical principles of human balance control. Eventually, this could help develop better bipedal robots, leg prostheses, and therapies for patients with balance disorders.

References

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