

A CASE STUDY ON BALANCE RECOVERY IN SLACKLINING

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The purpose of this study was to identify and describe the basic balance recovery movements performed during slackline balancing. Slacklining is an activity where the athlete balances on a thin piece of webbing that is mounted between two fixed points in a not too tight way. We designed an experimental setting where a controlled perturbation is applied to the slackline and study the movements of athletes to regain a balanced position. Four athletes took part in the study and for each we recorded five trials using a Vicon motion capture system. With the help of a 15 segment biomechanical model we studied mechanical quantities like the center of mass trajectory, the energy contributions, and also analyzed joint actuation patterns.

KEYWORDS: balance, slackline, motion control

INTRODUCTION: Slacklining is an activity where an athlete balances on a 2.5-5 cm wide piece of nylon webbing stretched between two anchor points. In contrast to tightrope walking, a slackline is only moderately tightened and allowed to stretch and bounce. Setups include “normal” lines of roughly ten meters that are close to the ground, long lines of up to 250 meters, high lines up to 1000 meters over ground and jump lines that allow tricks like rotations and flips.

The purpose of this study is to explore the underlying processes that allow the athletes to stabilize their bodies in this highly unstable setting.

METHOD: The research questions arising are manifold. How does the subject deal with perturbations on such a slackline? Which joints are actuated to regain a stable position? How far can the center of mass be deflected from the (unstable) equilibrium on the line before the subject falls? How much energy can be dissipated?

In order to address those questions a slackline (with 6.9 meters length, 0.46 meters above ground, with a pre-tension of 4000 Newton, leading to a maximum slack of 0.3 meters) was set up in a local gym. The line was laterally deflected at 0.53 meters from one fixed point using a ratchet system. The subject places itself on the slackline such that it is unable to anticipate the release of the deflection mechanism. After reaching a balanced position the deflecting rope is cut and a lateral perturbation is introduced into the system. The balance recovery movements are then measured and analyzed. Four slackliners with medium to very high skill levels took part in this experiment, each of which performed five trials.

We use a Vicon V612 motion capture system with eight near-infrared cameras and 100Hz sampling frequency. The subject is equipped with 55 spherical (14mm diameter), retroreflective markers. Another 12 markers are mounted on the slackline and the deflection mechanism and an additional 3D accelerometer (sampling at 100Hz) is also mounted on the slackline at the application point of the perturbation.

In order to determine body segment inertia parameters 95 anthropometric measures are taken according to Yeadon (1990) and joint coordinates are determined using a Global Optimization approach (Lu & O'Connor, 1999). Measurement artefacts are reduced by applying a modified zero-lag Butterworth filter with 10Hz cut-off frequency.

RESULTS: In general, two slightly different behaviours are shown by the test persons. While two of them balanced with two feet on the slackline before introducing the perturbation the other two balanced on one foot only. Results in this section are concentrated on the latter method, but do generally also agree with the former one.

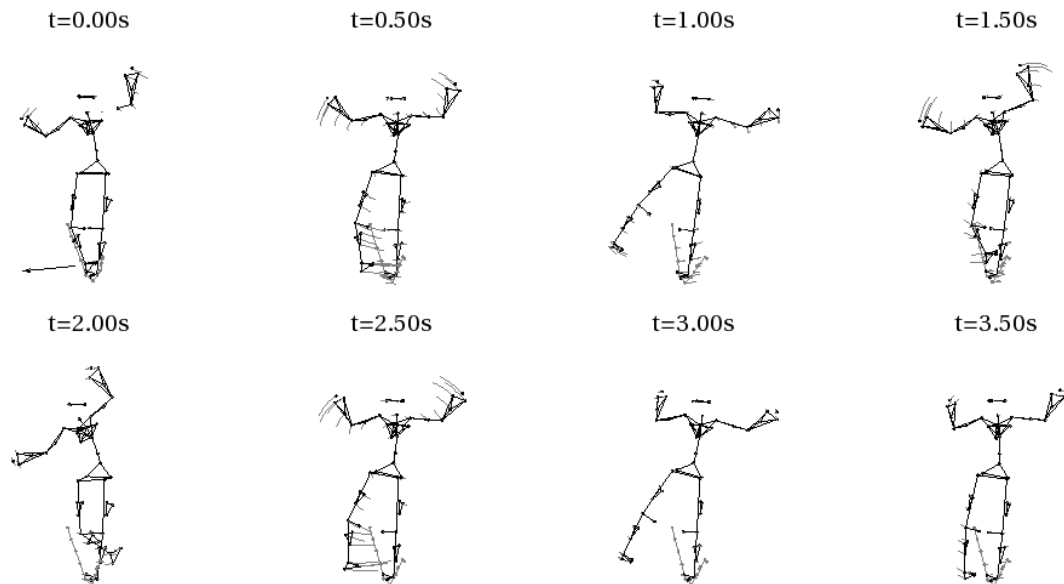


Figure 1. The reconstructed positions of markers on the subject and the slackline at times ranging from $t=0s$ to $t=3.5s$ viewed from the back for trial A. The marker trajectories during the preceding 0.2s are also included. At $t=0s$ the line is released and moves in the direction of the arrow to the original position.

In Figure 1 marker positions after the release of the deflection mechanism ($t=0$) are shown in 0.5s intervals, where the athlete is viewed from behind. In this trial (denoted trial A) the subject experiences a perturbation in the line such that the right foot is pushed to the left. The center of mass (CM) is no longer close to the equilibrium point. In order to regain a balanced position the subject has to rearrange the CM, the support point on the line (in this case the right foot) and the line's fixed points in a plane spanned by the vector between the anchor points and the vector of the gravitational force. A clockwise rotation of the whole body is seen within the first second. Several oscillations of the body are seen thereafter. About four seconds after release the subject has regained a configuration where only small corrections are needed to stay on the slackline. Acceleration peaks of 35 m/s^2 were recorded over the first 0.2 s and the slackline travelled 5 mm after release. The same information is shown for an unsuccessful trial (denoted trial B) in Figure 2.

In Figure 3 the center of mass (CM) component in x direction (perpendicular to the line and parallel to the ground) as well as the x-component of the center of the supporting foot is displayed against the time after release for the successful trial A (left figure) and the unsuccessful trial B (right figure). In the successful trial the leg undergoes rapid oscillations, which decrease in magnitude after around two seconds. In the unsuccessful trial the CM is displaced too far from the equilibrium position in the beginning of the counter movement, which leads to a fall shortly thereafter. Note that in trial A the trajectory of the supporting foot oscillates roughly around the CM path, which leads to forces in both directions, while in trial B no equilibrium restoring forces occur.

The total energy of the subject (i.e. kinetic and potential contributions) is plotted for trial A and B in Figure 4. In the successful trial A a peak in energy appears shortly after releasing the displacement mechanism and is dissipated in consecutive steps. After three such oscillations we arrive at an energy level comparable to the level before the perturbation. On the contrary for trial B a sharp rise in energy appears shortly after applying the perturbation and cannot be dissipated anymore.

Uncertainties in the results arise mainly from fluctuations in the reconstructed marker trajectories, soft tissue movement artefacts and uncertainties in anthropometric quantities and the applied model. In Figures 3 and 4 a band of uncertainty is included in the plot that is determined from measurement fluctuations, while we expect soft tissue movement contributions to be suppressed due to the use of the Global Optimization approach. Modelling uncertainties still need to be determined.

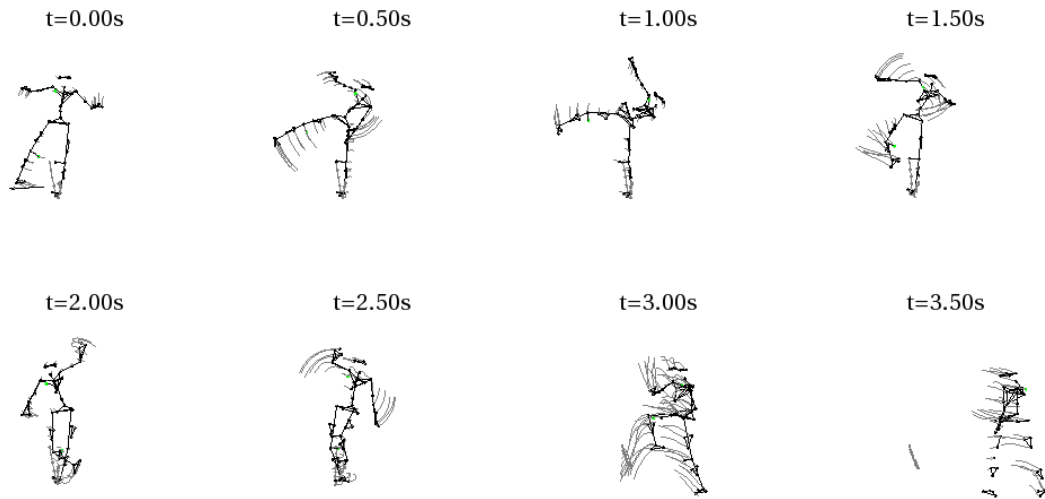


Figure 2. The reconstructed marker positions on the subjects and the line for the unsuccessful trial B.

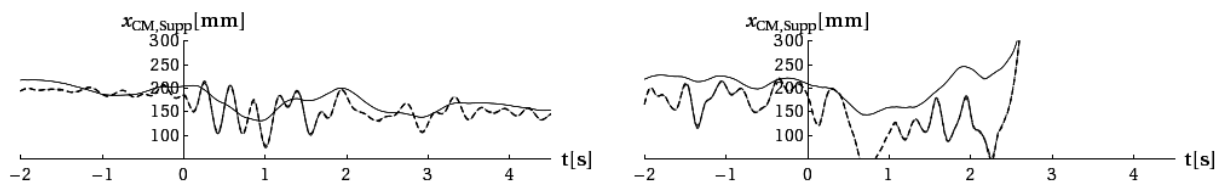


Figure 3. The x-components of the center of mass trajectory (solid line) and the supporting foot on the line (dashed line) for trials A (left) and B (right). An error band is included for both quantities, but it is hardly visible due to the small relative uncertainties of length measurements.

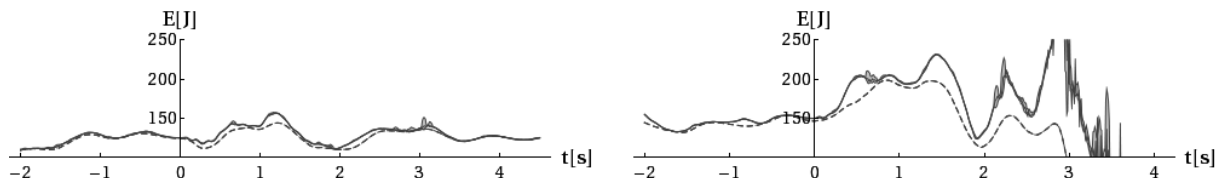


Figure 4. Potential energy (dashed line) and total energy (solid line, kinetic plus potential energy) of the subject plotted against the time after release for trial A (left) and trial B (right). In trial B the decrease in energy after 3.5 s appears because the subject had to step off the line. Note that the measurement uncertainties described above are displayed in form of an error band, which is mainly visible in the latter phase of trial B.

DISCUSSION: The presented results were collected in a pilot study with only a small group of experienced slackliners. Nevertheless, the basic mechanism of balance recovery movements can be identified. An equilibrium configuration of the system athlete/slackline is the combination where the two fixed points of the line, the support point of the body on the line and the athlete's CM are in the plane spanned by gravity and the fixed points. If the CM lies outside this plane there is a force driving the CM away from the equilibrium point. A change in body configuration and the elastic properties of the slackline allow the athlete to apply a force and angular momentum that can eventually restore the equilibrium position. Figures 1 and 2 suggest that the main contributions to this change in body configuration is due to movement in the arms. Depending on the technique applied also the non-supporting leg is used to balance.

Comparing the x-components of the CM trajectory and the supporting leg also provides an important insight to the mechanism of balance recovery. In order to experience a restoring force from the line it is necessary to assume a configuration where both, the CM and the

support point are displaced in the same direction normal to the plane described above. Due to the small damping in the system multiple oscillations of the line appear before a stable region is approached. Furthermore, none of the subjects managed to correct situations, where a lateral distance of more than 100mm between CM and the contact point on the line was measured.

After the release of the deflection mechanism the total energy of the subject increases. Although even with additional kinetic energy the athlete can stay on the line (which is also called "surfing" the line due to the swinging motion) it is easier to react to consecutive perturbations with minimal kinetic energy. The dissipation of energy is observed in an oscillatory way, which might be due to the elastic properties of the line.

On a different note, any basic knowledge on movement regulation patterns of healthy, well trained subjects under these highly unstable conditions may help to better interpret human balance regulations in general as well as balance disorders.

Slacklining could also improve balancing capabilities in other sports and therapy. A possible way to study effects would be to measure and analyze balancing capabilities in quiet standing (e.g. by means of nonlinear analysis, Cagran et.al. (2010)) before and after basic slackline training.

CONCLUSION: We present results of a pilot study to address the mechanism underlying balance recovery on a slackline. A lateral perturbation is introduced into the system and the reaction of the test person was studied. Basic mechanical quantities, e.g. the center of mass trajectory and energy contributions were computed. As expected from experience all subjects predominantly used their arms to react to displacements of the center of mass. Measurements also show that energy due to the counter movements is dissipated in a stepwise fashion. Also none of the subjects were able to regain balance when the center of mass was further than 100 mm away from the contact point on the line in lateral direction.

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