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A rule of thumb for safe midline backups.

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Introduction

Slacklining is a relatively new sport. In the last decade the number of people who practice it has been increasing exponentially, world records are being broken at an alarming rate and the frontiers of the sport are rapidly expanding beyond what was previously unthinkable. However, to date (2017) there is no official qualification for instructors, nor do there exist respective safety courses, as e.g. for backcountry skiers and divers. This article aims to be a small step towards safer practices and better understanding of the risks.

In a particular flavor of the sport, called highlining, in which the line is rigged high off the ground, the practitioners walk and play on the line connected to it —for safety— with an umbilical cord (the leash) tied on a sliding ring. A safe highline rig must always include a backup system serving to keep the slackliner off the ground in the event of main line failure. The backup consists of a completely redundant line running in parallel to the main line and fixed to separate anchors. When the distance between the highline and the ground is relatively small, the backup line has to be well tensioned in order to be effective. The minimum required tension depends dominantly on: the length of the highline (in this case referred to as *midline*), the height of the anchor points from the ground (assumed horizontal), the elasticity of the backup material (effective modulus), the length of the leash, and the mass of the person. Using basic physics and a number of approximations it is possible to derive a theoretical estimate of the minimum required tension. However, the effective modulus of the backup material depends on its age and history of use, as well as on other environmental factors (temperature, humidity). In addition, visco-elasticity effects modify the behavior of the backup material. Even if the dynamical characteristics of the specific webbing were known from the manufacturer, taking into account all the above-mentioned factors is very difficult, particularly so on the field. Moreover, even if the backup line had a perfectly predictable elastic behavior, to provide a valid estimate of the minimum required tension with a reasonably small bounded error, a number of variables need to be determined with adequate accuracy using instrumentation that is rarely available in the field.

For all these reasons, and for the shake of simplicity, a rule of thumb for backup safety is presented here bypassing some of the above-discussed difficulties. This rule overestimates the required height, which only increases the safety margin. The widely circulated article of the International Slackline Association (ISA) "*Midlines - low highlines*" by Thomas Buckingham, Philipp Gesing and Daniel Laruelle, presented an earlier version of this rule of thumb as derived by the author (Panos Athanasiadis) in 2013. In the present, this rule of thumb is reviewed and modified with some vital corrections. Validation is provided by testing experiments performed for different materials and midline geometry.

Derivation

A pretensioned backup is an all necessary component of a safe midline. In the event of a leash fall on the backup system alone, due to main line failure, the higher the pretension of the backup line the shorter the fall will be. However, a very tight backup is generally unwanted. Then, what is the minimum backup pretension that will keep us from hitting the ground for a given midline set up? Or, the same problem posed differently, what is the minimum required height of a given midline for a certain backup pretension? An answer to this problem is given here using energetic arguments and making careful approximations for the benefit of safety and simplicity. It is worth noting that the length of the midline does not enter this rule.

When the person falls the gravitational potential energy of her/his body will turn into kinetic energy and strain energy absorbed by the backup system. It can be assumed that all the kinetic energy is eliminated when the body reaches the lowest point (assumption I). Also, we can assume that the upward force exerted by the backup system to the body (through the leash) is proportional to the vertical displacement of the leash ring from the level of the anchors (assumption II). In that case, if S is the measured static sag of the backup system (supporting alone the body weight, Fig. 1), it should be $mg = KS,$ where K is the respective effective stiffness (a virtual modulus).

Let's take that H is the vertical distance from the anchors to the ground (assumed flat, Fig. 1), L is the length of the leash (harness to ring), λ is half the body height (supposing that the attachment point of the harness is near the center of gravity of the body) and Y is the lowering of the backup (leash ring) in respect to the anchors at the lowest point of the trajectory of the falling body (Fig. 2). Supposing that when the main line fails the center of gravity of the body is above the level of the anchors by a distance λ (assumption III), a sufficient condition for not touching the ground can be expressed as

$$H > Y + L + \lambda. \tag{1}$$

For the same initial height of the body (assumption III), the vertical distance traveled by the ring at the lowest point of its trajectory will be maximum if the fall takes place at the midpoint between the two anchors. Assuming that this is the case, the maximum lowering of the backup (Y) can be determined using the conservation of energy. Given the above-made assumptions (I, II and III) the conservation of energy gives

$$mg(Y + L + \lambda) = \frac{1}{2}KY^2. \tag{2}$$

Substituting mg with KS, the last equation can be written as

$$Y^2 - 2SY - 2S(L + \lambda) = 0. \tag{3}$$

This quadratic equation for Y has only one positive root, which reads

$$Y = S + \sqrt{S^2 + 2S(L + \lambda)}. \tag{4}$$

Therefore, the condition expressed by Eq. 1 becomes

$$H > S + L + \lambda + \sqrt{S^2 + 2S(L + \lambda)}. \tag{5}$$

It can be shown graphically that the above condition is more strict —and thus safer— than the safety rule of thumb previously proposed by the author and published by ISA (Buckingham, Gesing and Laruelle, 2013). Keeping in mind that a rule of thumb should be safe but also simple, instead of the above-derived condition (Eq. 5) the following approximation is proposed as a replacement to the old rule,

$$H \; > \; 2(S + L + \lambda). \tag{6}$$

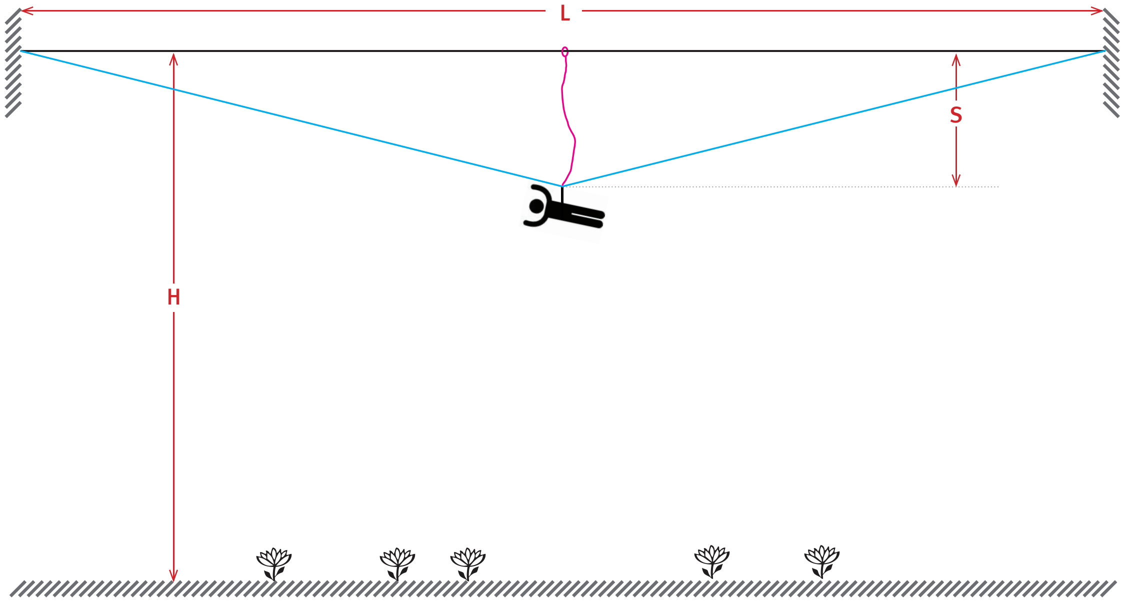

Figure 1: The backup sag (S) is defined as the lowering of the backup line when weighted at its midpoint by the heaviest person in the group. This distance can be easily measured by attaching oneself to the backup line and rappelling down from the mainline until all the weight is transferred (rappel line gets loose). Alternatively, the backup line can be pulled down applying the same weight from the ground.

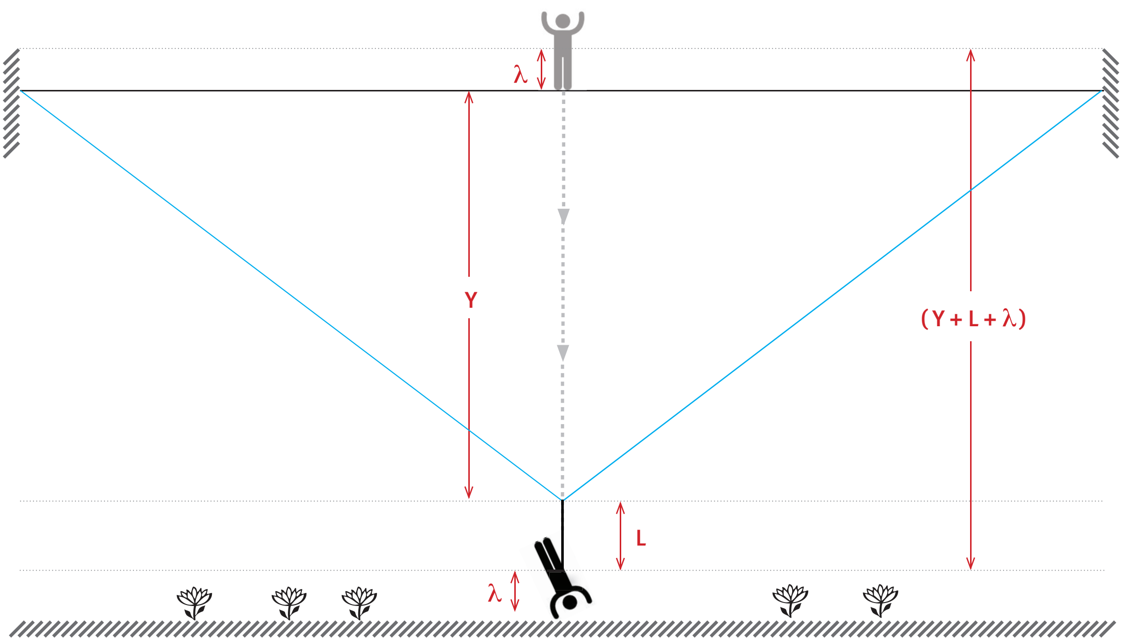

Figure 2: The height of the midline from the ground should be greater than the maximum vertical distance traveled by the center of mass of the body $(Y + L + \lambda)$. Using a set of assumptions this simple condition leads to the rule of thumb: $H > 2(S + L + \lambda)$, where S is the measured backup sag (Fig. 1), L is the length of the leash and λ is half the body height.

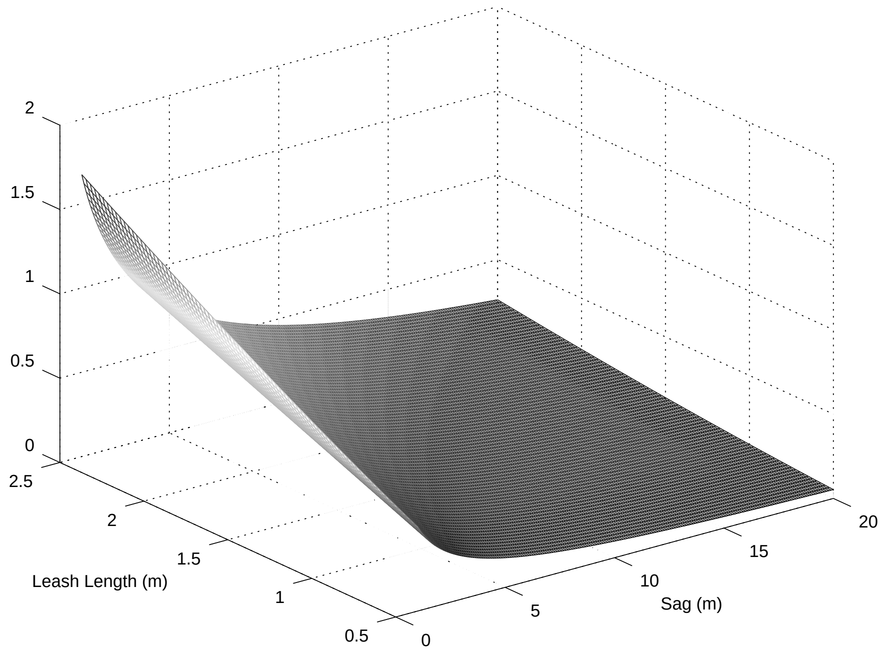

Figure 3: The overestimation of the necessary height (H) by the new approximate rule of thumb (Eq. 6) in respect to the more accurate derived condition (Eq. 5) as a function of the sag and the leash length. This always positive overestimation adds to the safety margin.

Discussion

This new rule of thumb (Eq. 6) leads to a small overestimation of the necessary height H in respect to the less easy to use above-derived condition (Eq. 5). Figure 3 shows the overestimation (which further adds to the safety margin) as a function of the sag and the leash length. It should be noted that for typical leash lengths ($\sim$1.5m) and realistic sag values ($>$1m) the overestimation is very small (less than 1m). This is acceptable, but what about the above-made assumptions?

Assumption I: At the lowest point there is always some left-over kinetic energy related to the acquired horizontal velocity and spin, hence less energy has to be absorbed by the backup. Ignoring this left-over kinetic energy increases the safety margin.

Assumption II: This corresponds to the small-angle approximation used to analyze small perturbations on a string, where the tension is assumed constant. In reality, the vertical projection of the backup tension increases faster than linearly with the vertical displacement (Athanasiadis, 2017). Effectively, this assumption ignores a non-linear (cubic) term that becomes increasingly important as the vertical displacement grows. Ignoring this term significantly simplifies the dynamics and only adds our safety.

Assumption III: Due to the main line sag, when the main line fails the center of gravity of the slackliner is more likely to be below than above the anchors. Hence, this assumption strongly increases our safety margin since, in reality, the gravitational potential energy to be absorbed during the fall will always be smaller than what is assumed here.

Furthermore, there are some other effects working in favor of our safety: (*i*) the modulus of the backup media (rope/webbing) generally increases with the applied tension and under dynamic loading[1], and (*ii*) as it is unlikely for the person on the line to fall exactly at the midpoint, chances are that during the fall the leash ring will slide along the backup providing additional (frictional) dissipation and thus lowering the energy that remains to be absorbed dynamically by the backup system.

Eq. 6 presents a new safety rule of thumb for midlines. Apparently, one has to measure the backup sag, which in some cases may require more effort than measuring the backup pretension. Yet, by measuring the backup pretension one cannot compute the fall height without knowing also the stretch characteristics of the backup material (rope / webbing) in the given circumstances. Instead, the application of the rule of thumb presented here does not require any measuring instrument, such as a load cell. Moreover, directly measuring the backup sag provides a more reliable estimate of its elastic response under the given conditions. Finally, it is worth noting that the presented rule of thumb does not involve the length of the midline.

Most often than not the hight of the anchors from the ground (H) cannot be altered. In this case one has to determine the maximum backup sag that will satisfy the inequality of Eq. 6.

[1] The effective modulus of the backup material (rope / webbing) should not be confused with the fictitious modulus K introduced to express the vertical restoring force.

Namely, solving for the sag we get

$$S < \frac{H}{2} - L - \lambda. \tag{7}$$

One should not be concerned about the elongation of the leash. However, one can always add a 25% elongation to the leash in the application of the rule of thumb (Eqs. 6–7) to account for knot slippage and stretch.

Also, it is important to leave the backup system tensioned for a while before measuring its sag, as well as to let the heaviest person of the group do this measurement. How to do it? Well, one can always go to the midpoint, attach himself/herself to the backup with a carabiner and safely rappel down from the main line until all the body weight is on the backup. This way, as the main line returns to its free-standing point, the piece of rope used for the short rappel can be used as a tape measure for determining the backup sag against the quasi-horizontal main line.

Experimental verification

The presented rule of thumb was carefully tested by Panos Athanasiadis and Witek Gawlik. A truck tire of 70kg was raised above the level of the tensioned backup line and was left to fall at the midpoint with a static leash of 1.5m. The ground was flat, and the height of the anchors from it was 9m. The experiment was repeated for two anchor-to-anchor distances: 22m and 38m. The backup line consisted of a 10.5mm static rope (Tendon). For the 38m distance, the test was repeated using also a polyester webbing (Landcruising Core 2 LS).

In all cases the pretension of the backup was adjusted so that its sag complied to the rule of thumb (Eq. 7). It was observed that at the lowest point of its trajectory the tire always had substantial clearance from the ground. It is worth noting that even the previous version of the rule of thumb, $H > 2(S + L)$, which ignores the height of the person, did pass the test. However, to account for inaccuracies in measuring the backup sag and for the fact that the backup tension may drop with time due to creep and the probable leash falls, it is recommended to use always the present updated version.

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