Functional Hazard Analysis of a Helicopter-based Highline Rescue Using a Longline

Version 2.0 by Jakob Bludau, Aaron Benkert, Lukas Irmler,
and Michael Seemann

October 17, 2024

Contents

1 Introduction

A Highline rescue is similar to one of a lead climber, a highly technical rescue. Furthermore, the patient is prone to suspension trauma due to long periods of hanging in a harness. Therefore, time is a priority. Highlines span gaps, ridges, etc. Often, the anchors are only reachable by rappel/climbing. Thus, even if a terrestrial rescue transports the patient to one of the anchors, the way to a hospital is still long. Furthermore, the mode of transport to the hospital is probably a helicopter due to the terrain.

With longer Highlines, the rescue is escalating in complexity. Ropes need to be longer, and direct rappel off the Highline is no longer possible or dangerous (stretch in "static" ropes and webbings is not negligible and leads to large vertical movement during rappel). Furthermore, rescuers must pull the patient up for a rescue towards one of the anchors due to the Highline sag.

These thoughts lead the authors to discuss a helicopter-based rescue directly off the Highline with Heli Austria (namely Gabriel Falkner). A literature review showed that there is little published experience on this topic.

This document contains the thoughts of the authors on a helicopter-based highline rescue. The document shows the stages of the procedure in section 2, based on the procedure for an injured lead climber. Section 3 describes the conventional setup of a Highline. The authors derived a functional hazard analysis of the rescue procedure in section 4. Section 4 also contains mitigation measures for the most critical risks. Section 5 describes the resulting Highline setup for safer training. Finally, section 6 lists the procedure and the personal protective equipment in detail. The overall focus is on safety.

This document targets a rescue with a longline as a connection between rescuer and helicopter. Inferring from the contact of climbing ropes with the Highline, the authors suspect the textile longline rope with a diameter of approx. 20mm to have a negligible chance of cutting the Highline. If a thin steel hoist cable used for rotorcraft-based rescue poses a severe threat

2 Procedure of lead climber rescue as starting point

This document starts with a procedure similar to rescuing a lead climber hanging in a harness from a rope. The load-bearing path defines the phases of this procedure. (The names of the phases are in bold font in the following list)

- 1st: **Approach and positioning** of the rotorcraft, including rescuer and rescue equipment above the patient.
- 2nd: Rappel of rescuer and **attaching of the patient's harness** to the longline.
- 3rd: **Climb of the rotorcraft** to transfer the patient's load off the climbing rope onto the longline.
- 4th: **Cutting of the climbing rope** and check that the patient and rescuer are only connected to the rotorcraft.
- 5th: **Departure** towards a free direction.

From the start of phase 2 until the end of phase 4, the rescue equipment, the harness of the patient, and the climbing rope connect the rotorcraft to the terrain. Nevertheless, the stretch and slack of the climbing rope allow movement in a limited range.

During phases 1 and 2, the load-bearing paths of the rescuer and the patient are entirely separate. During phase 3, the patient's load is gradually transferred to the longline. The transfer is complete if the climbing rope is free of load. After the climbing rope cut in phase 4, the rotorcraft carries the load of the rescuer and the patient.

This procedure works for a Highline rescue with a few minor modifications. These modifications result from the functional hazard analysis in chapter 4. The following shows the resulting procedure. Italics highlight differences between the procedure and the lead climber rescue procedure.

- 1st: **Approach and positioning** of the rotorcraft, including rescuer and rescue equipment above the patient.
- 2nd: Rappel of rescuer and **attaching of the patient's harness** to the longline.
- 3rd: **Climb of the rotorcraft** to transfer the patient's load off the *Highline* onto the longline. *Furthermore, the rescuer positions the rotorcraft approx. 1m of horizontal distance to the Highline to check if any unwanted connection to the Highline exists.*
- 4th: **Cutting of the** *leash* and check that the patient and rescuer are only connected to the rotorcraft.
- 5th: **Departure** towards a free direction.

3 Conventional highline setup

Conventional Highlines consist of two anchors, a main line, one backup line, a leash ring, the leash, and the athlete's harness. Suitable points for anchors are trees, bolts, and removable equipment like cams, ice screws, or nuts. Anchors are generally redundant.
The main and backup lines are hung between the anchors. Personal preference, in combination with the used material, determines the pretension of the main line. The backup line prevents a fatality in case of a mainline failure due to falling debris or friction. It hangs loosely underneath the main line, often in loops. In case of a main line failure, the backup is an entirely redundant connection to the terrain. Nevertheless, this requires sufficient free horizontal distance underneath the line.
The main and backup lines go through a closed metal loop called the leash ring. The leash ring is an attachment point that can move along the line. The athlete connects the harness to the leash ring via a 1.2m long leash. This leash often consists of a climbing rope fed through a tubular webbing for redundancy.

4 Functional hazard analysis and risk mitigation for a safe training setting

Two outstanding dangers are present during all phases of the rescue:

- The backup line, a secondary line that runs parallel to the main line, is a crucial component in the rescue operation. It serves as a safety measure in case the main line fails. However, it's important to note that the backup line can also pose a potential danger of entanglement, as its loops can wrap around arms, legs, or material (on the harness, the longline rig, etc.). This can lead to complex problems that are difficult to solve. In a training environment, using a tubular material that both main line and backup go through is essential to eliminate the danger of entanglement.
- In the event of a main line rupture, the line snaps back towards the anchors. This snapping action is more pronounced in what we refer to as "high slack settings", where there is a significant amount of slack in the line. To reduce the risk of line rupture, the slack of a training line is reduced by increasing the tension in the main line. This, in turn, increases the distance between the main line and the rotorcraft, minimizing the potential for the line to snap back towards the rotorcraft.

The following Functional Hazard Analysis lists the risks of every procedure phase separately. It distinguishes between the functional systems *rotorcraft*, *longline*, *harness*, *leash*, *rescuer*, and *highline*. As the patient might be unconscious, no functions are associated.
The risks result from errors/inabilities of the listed systems during the rescue phases. This document lists the expected criticality of the identified risks in all phases of the rescue and proposes mitigation to create a safe training environment.
The text uses *highline* for the system composed of the two anchors, the main and backup line, and the leash ring as this system fulfills the functions **load bearing** and **psotitioning** as a single unit. Nevertheless, the risk lists a breakdown in the description if necessary.
This document gives the criticality of a risk on three levels low, medium, and high. The levels encode the complexity that a solution to the problem requires and the potential harm for rescuers, patients, and rotorcraft. Table 1 gives the different levels.

criticality	complexity of solution	potential harm
low	no actions necessary	none
medium	1-2 simple steps, visual check, known communication	small bruises on arms or legs
high	cutting, thinking thinking, spontaneous problem solving/communication	everything more than small bruises on arms or legs

Table 1: Levels of criticality described by their complexity and potential harm.

Table 2 gives the functions of the individual systems:

system	function
rotorcraft	load bearing positioning (with help of rescuer)
rescuer	positioning (self,rotatoric) positioning (self,translatoric) attaching patient to longline cutting connection patient to highline
longline	load bearing
highline	load bearing positioning
leash	load bearing
harness (patient)	load bearing

Table 2: Systems and respective functions.

The analysis does not differentiate between different causes of a failure of the rotorcraft to provide the functions **load bearing** and **positioning**. The rotorcaft corresponds to a black box system that can change the position in 3D space and lift a load (load bearing). In case of an emergency, the rotorcraft can drop the longline.

Humans perform some of the mitigation that is identified by the analysis. Therefore, the three roles rescuer, patient, and external observer are defined. All humans involved in the training are connected via a shared radio.

4.1 Phase 1: Approach and Positioning

This phase starts when the systems rotorcraft+rescuer+longline interacts with the systems patient+highline. This includes aerodynamic interactions (e.g., downwash onto a highline).
Risks that originate solely from using a rotorcraft+rescuer+longline during the approach are **not** included here.

System:	Affected function:	Criticality:	Number:
Rotorcraft	Load bearing	high	1.1

Possible causes:
Power or control deficit of rotorcraft

Description:
A power or control deficit of the rotorcraft during the positioning of the rescuer relative to the patient can occur, which causes the rotorcraft to lose altitude. This poses the risk of unintended contact between the longline and the highline.

Mitigation:
- abrasion-resistant tubing around highline and backup
- Highline with abrasion-resistant ropes as backup
- Approach of the rotorcraft to the highline from the side to which it can depart while autorotating at all times

Criticality with mitigation:
medium, as the tubing prevents abrasion of main line and backup. With ropes as backups, it is less prone to damage from hitting objects. Approach from the departure side allows the rotorcraft to cancel the rescue and depart at all times.

System:	Affected function:	Criticality:	Number:
Rotorcraft	Positioning	high	1.2

Possible causes:
e.g. approaching to low/left/right relative to patient, present turbulence, recirculation, etc.

Description:
During the positioning of the rescuer relative to the patient abrasive contact between longline and highline is possible. This could damage the main line. Furthermore, the contact between longline and highline might change the handling quality of the rotorcraft

Mitigation:
- abrasion-resistant tubing around highline and backup
- Highline with abrasion-resistant ropes as backup
- Canceling the rescue mission if the pilot or rescuer have concerns

Criticality with mitigation:
medium, as the tubing prevents abrasion of main line and backup. With ropes as backups, it is less prone to damage from hitting objects. Approach from the departure side allows the rotorcraft to cancel the rescue and depart at all times.

System:	Affected function:	Criticality:	Number:
Rescuer	Positioning (transl.)	high	1.3

Possible causes:
Rescuer positions themself on the wrong side of the highline, thus preventing an unhindered departure of the rotorcraft. Rappel device can get entangled in the highline or backup

Description:
During the rappel of the rescuer, they could end on the side of the highline that does not correspond to the departure direction of the rotorcraft, which prevents the rotorcraft from departing unhindered. When rappelling too far, the longline might be pulled vertically along the line, which is discussed in 1.2

Mitigation:
- Communication between pilot and rescuer, slow approach
- Rappel with variable longline on the departure side of highline
- Patient, and external observer intervene on radio in case of rappel errors

Criticality with mitigation:
medium, as the approach to the patient is similar to other maneuvers. Patient, and external observer can observe and intervene from different viewpoints Rescuer can reach the rappel device and remove connections with the highline

System:	Affected function:	Criticality:	Number:
Rescuer	Positioning (rot.)	high	1.4

Possible causes:
Rescuer and patient are in contact, wake of rotorcraft causes twisting of rescuer and patient. This results in longline and leash being twisted, at extreme connecting both.

Description:
During the contact of rescuer and patient, an unwanted twist of leash and longline could end in an unwanted connection of the rotorcraft to the highline. Depending on the number of twists, untangling can require extensive work. Furthermore, the twisted ropes can prevent further rappelling or lifting of the rescuer relative to the patient

Mitigation:
- Rescuer grabs patient with legs
- Manually distancing leash and longline helps to prevent twisting
- Patient, and external observer intervene on radio in case of dangerous twisting

Criticality with mitigation:
medium, as the patient can intervene and push the leash and longline apart, which prevents the twisting.

The functions “Connecting patient’s harness” and “Cutting the connection between patient and highline” must not be executed during this rescue phase. Any attempt to do so must result in an immediate abort of the procedure.

System:	Affected function:	Criticality:	Number:
longline	load transfer	high	1.5

Possible causes:
Helicopter has to release longline

Description:
During the positioning of the rescuer to the patient by helicopter, it may be necessary for the helicopter to release the longline. This could put strain on the highline from the falling longline and rescuer. The problem is that the highline can be subjected to multiple impacts by the falling rescuer and longline. In addition, the weight of the rescuer could pull the longline over the highline and cause damage.

Mitigation:
- Abrasion-resistant coating of line and backups
- Line construction with multiple backups made of core-sheath ropes
- Avoid having rescuer and helicopters on different sides of the highline

Criticality with mitigation:
medium, as the sheath prevents friction damage to the line. Damage caused by hitting can be mitigated by the backups used.

System:	Affected function:	Criticality:	Number:
Highline	positioning	high	1.6

Possible causes:
Aerodynamic interaction of highline with helicopter downwash (rocking of the line in the wind)

Description:
Aerodynamic interaction between the helicopter and the highline is possible even before the rescuer can reach the patient. Since long highlines can swing strongly sideways and have little damping in this direction, this can prevent the helicopter from positioning the rescuer with sufficient accuracy. Furthermore, the downwash can cause the loops of the highline backup to swing around and get caught in various places on the patient or rescuer. These unwanted connections have to be cut during the subsequent rescue process. If not released they could lead to unwanted tied-up situations.

Mitigation:
- Termination of the attempt in case of acute swinging of the highline
- Hovering near highline to test aerodynamic interaction (careful approach)
- Sheathing the highline and backups to eliminate loops
- Higher highline tension than usual to reduce swinging

Criticality with mitigation:
medium, as the formation of loops is prevented and a slow approach to the final position of the helicopter allows an abort at any time

System:	Affected function:	Criticality:	Number:
Highline	load transfer	high	1.7

Possible causes:
Rockfall or other objects blown down by downwash

Description:
A falling stone, branch, carabiner, etc., is enough to cut the highline under tension. This causes the patient to fall into the backup and hang lower than if hanging the highline. Several objects could fall down in a row and also cut off the backup that is subsequently loaded.

Mitigation:
- Use of two core-sheath ropes as independent backups
- The double backup distributes the load parallel to both strands
- Cleaning the anchors of loose stones and objects that could be thrown up

Criticality with mitigation:
medium, since a sequential cutting of line and two impact-resistant core-shell ropes are considered very unlikely to be damaged by falling objects (since the cutting sensitivity also decreases with decreasing load)

System:	Affected function:	Criticality:	Number:
Leash	load transfer	high	1.8

Possible causes:
No causes for spontaneous leash rupture known

Description:
Spontaneous tearing of the leash due to contact with a sharp object under load. This is generally eliminated by the construction of a leash, which is made of climbing rope and enveloping tubular band with the same load capacity. However, it is included in the analysis because a simple leash can be used for easier cutting in a training scenario

Mitigation:
- Avoid sharp objects on harnesses/clothing of rescuer and patient
- Additional self-belay loop that can be hung in the leash ring if the leash is damaged unintentionally

Leash shorter than the patient arm's length so that the leash ring can be reached while sitting in a harness

Criticality with mitigation:
high, but very unlikely. Even with a simple leash when wearing suitable clothing and harnesses.

A failure of the patient's and rescuer's climbing harness will not be discussed here, as this is considered unlikely when using an undamaged harnesses.

4.2 Phase 2: Attaching the patient's harness

System:	Affected function:	Criticality:	Number:
helicopter	load transfer	high	2.1

Possible causes:
(Temporary) performance deficit of the helicopter

Description:
Before attaching the longline, this is described in 1.1. After attaching the longline (helicopter tied up), the rescuer's load can also be transferred to the highline via the connection between longline, patient's harness and leash if the helicopter accidentally loses altitude. The longline can be unloaded and released if the helicopter has to leave its hovering position during this phase. Furthermore, the longline can be dropped and the rescuer falls into the highline together with the patient. However, the falling longline can harm personnel and the highline (impact and friction on the highline).

Mitigation:
- Abrasion-resistant coating of highline and backups
- patient and rescuer wear an appropriate helmet
- Line construction with multiple backups made of core-sheath ropes
- Sufficient fall height under the highline for line stretch by the weight of two persons
- Terrestrial rescue equipment and an easily accessible highline anchor
- Sufficient personnel with knowledge at the anchors for a terrestrial rescue

Criticality with mitigation:
high. The sheathing prevents friction damage to the line. Damage caused by impact can be mitigated by the backups used. Injury to people caused by falling ropes cannot be ruled out, but immediate, rapid rescue can be prepared. The helmet offers head (and eye) protection. A sufficient fall height can be planned for when setting up.

System:	Affected function:	Criticality:	Number:
helicopter	positioning	high	2.2

Possible causes:
Tied-up helicopter steers the highline due to position fluctuations

Description:
During the positioning of the rescuer to the patient by the helicopter, relative movement with contact between the longline and the highline could occur for various reasons. This could cause friction damage to the highline. Furthermore, the contact between the line and the longline could affect the control behavior of the helicopter. In the most serious case, the longline could have to be released (in this case, see 2.1)

Mitigation:
- Abrasion-resistant coating of line and backups
- Line construction with multiple backups made of core-sheath ropes

Criticality with mitigation:
medium, as the sheath prevents friction damage to the line. Damage caused by hitting can be mitigated by the backups used. Releasing the longline does not cause the rescuer to fall

System:	Affected function:	Criticality:	Number:
rescuer	positioning (transl.)	high	2.3

Possible causes:
Flight rescuer positions himself too far below patient to attach patient to rope.

Description:
Immediately after attaching the patient, the rescuer can lower himself too far with the variable longline or hang below the patient due to the helicopter losing altitude. This can be so much that the longline is unloaded and patient and rescuer hang vertically above each other. In this state, twisting of the longline and leash can no longer be effectively prevented.

Mitigation:
- Slow lowering on the variable longline to avoid ending too far below the patient
- Early warning of the pilot about any unintentional descent of the helicopter
- observer and patient intervene early by warning on the radio (air rescuer too low)
- If the longline is unloaded, the patient grabs the highline to prevent twisting.

Criticality with mitigation:
medium, as it can be prevented by the patient with a short leash (highline within arm's reach).

System:	Affected function:	Criticality:	Number:
rescuer	positioning (rot.)	high	2.4

Possible causes:
The rescuer and patient are in contact, the downwash from the helicopter causes them to twist and thus, the rope and leash can get twisted if the rescuer does not take adequate action.

Description:
Even if the rescuer is not positioned too low below the patient, the leash and rope can become twisted. During the rescue, the flight rescuer should prevent this to avoid an unwanted restraint situation.

Mitigation:
- Air rescuer safely grasps patient with legs in case of contact
- Twisting can be made more difficult by the rescuer pushing the leash and rope apart (approx. 50cm).
- After the patient has been safely attached to the rope, the helicopter can create a horizontal distance of approximately one leash length between the highline and the rope. This aides in identifying unwanted connections and effectively prevents twisting of longline and leash.
- observer and patient intervene early via radio warning

Criticality with mitigation:
low, as the patient can intervene early, and twisting can be stopped by the patient grabbing the highline.

System:	Affected function:	Criticality:	Number:
rescuer	Attaching the patient harness in longline	medium	2.5

Possible causes:
rescuer hangs too low/high or too far to the side of the patient to attach his harness to the rope

Description:
During the attachment phase, various readjustments of the position of the air rescuer may be necessary to attach the patient. This increases the time and, thus, the risk in this phase. Furthermore, the patient's harness may be attached incorrectly due to the lack of visibility on the harness/leash/line/etc.

Mitigation:
patient checks with rescuer whether he is correctly hooked in and communicates all related problems on the radio

Criticality with mitigation:
low, since the patient checks the situation by the four eyes principle. In case of a security risk, feedback is given, and appropriate action is taken

During this phase, the air rescuer is not allowed to carry out the function “disconnecting the patient from the highline”. If the timing is incorrect, the patient intervenes by issuing a warning on the radio. Since cases 2.1 and 2.2 already deal with the release of the rope in this phase, it will not be explicitly listed again here.

System:	Affected function:	Criticality:	Number:
Highline	positioning	high	2.6

Possible causes:
Aerodynamic interaction of highline with helicopter downwash (rocking of the line in the wind)

Description:
Aerodynamic interaction between the helicopter and the highline is possible even before the rescuer can reach the patient. Since long highlines can swing strongly sideways and have little damping in this direction, this can prevent the helicopter from positioning the rescuer with sufficient accuracy. Furthermore, the downwash can cause the loops of the highline backup to swing around and get caught in various places on the patient or rescuer. These could have to be cut during the subsequent rescue process or could lead to unwanted tied-up situations.

Mitigation:
- Test for upward-swinging behavior already in phase 1 (approach)
- Sheathing of line and backup to prevent loops in a training session

Criticality with mitigation:
medium, as the formation of loops is prevented, and a swinging up in phase 1 can be tested by a slow approach

System:	Affected function:	Criticality:	Number:
Highline	load transfer	high	2.7

Possible causes:
Rockfall or other objects blown down by downwash

Description:
A falling stone, branch, carabiner, etc., is enough to cut the line under tension. As a result, the patient suddenly falls into the longline and the line no longer supports his weight. This can lead to a high control load for the pilot. The length of the connection between the rope and the patient harness limits the height of the fall

Mitigation:
- Cleaning the anchors of loose stones and objects that could be thrown up
- Prohibit actions near the highline that involve throwing/kicking off objects/etc.
- Minimize the possible fall height of the patient in the event of a highline tear

Criticality with mitigation:
medium. It is very unlikely if the anchors are cleaned and personnel at the anchors are careful. In addition, the fall height can be kept small, and the pilot can be prepared

System:	Affected function:	Criticality:	Number:
Leash	load transfer	high	2.8

Possible causes:
Fall of two people into the leash when releasing the longline

Description:
If the longline has to be released during this phase, the rescuer and patient will fall into the patient's leash.

Mitigation:
- Avoid sharp objects on harnesses/clothing of rescuer and patient
- Cutting tool for the leash cut remains secured in a holder
- No unprotected, sharp objects on patient and rescuer

Criticality with mitigation:
high, but can easily be avoided by taking measures (use of suitable clothing and harness and appropriate caution).

System:	Affected function:	Criticality:	Number:
harness	load transfer	medium	2.9

Possible causes:
Fall of two people in the leash when releasing the longline

Description:
If the longline has to be released in this phase, the rescuer and patient fall into the patient's leash. The rescuer's load path is via the longline into the belay loop of the patient's harness. The leash is usually tied parallel to the belay ring (threaded through the loops of the harness, similarly to tying in a climbing rope).

Mitigation:
- Attach the longline to the leash attachment loop and the patient harness attachment ring.
If only one is possible, attach it to the leash attachment loop.
- patient checks that the rescuer has correctly attached the longline

Criticality with mitigation:
low. Can be controlled very well through communication and the 4-eyes principle.
However, a suitable communication channel is a mandatory

4.3 Phase 3: Climb of the rotorcraft to transfer load

This phase begins after the patient has been successfully hooked into the longline and the rescuer and patient are lifted by the helicopter. The lifting is complete when the highline is (almost) free of load.

System:	Affected function:	Criticality:	Number:
helicopter	load transfer	high	3.1

Possible causes:
(Temporary) performance deficit of the helicopter

Description:
After attaching the longline (helicopter tied up), the rescuer's load can be transferred to the highline via the longline, patient harness, and leash if the helicopter accidentally loses altitude. The load is gradually transferred from the highline. However, if the helicopter abruptly stops transferring the load, the highline can swing vertically. In this case, the longline could be periodically loaded and unloaded. However, since the patient and rescuer are still secured via the highline, releasing the longline does not lead to a person falling.

Mitigation:
- Abrasion-resistant coating of line and backups
- patient and rescuer wear an appropriate helmet
- Line construction with multiple backups made of core-sheath ropes
- Sufficient fall height under the highline for a fall with the weight of two persons
- Terrestrial rescue equipment and an easily accessible highline anchor
- Sufficient personnel with knowledge at the anchors for a terrestrial rescue
- Increased preload in the highline to keep the fall height low
- Pilot's awareness

Criticality with mitigation:
high. The sheathing prevents friction damage to the line. Damage caused by impact can be mitigated by the backups used. Injury to people caused by the falling rope cannot be ruled out, but immediate, rapid rescue can be prepared. The helmet offers head protection. A sufficient fall height can be planned for when setting up

System:	Affected function:	Criticality:	Number:
helicopter	positioning	high	3.2

Possible causes:
Tied-up helicopter steers the highline due to fluctuations in its hover position

Description:
During the lifting of the rescuer and patient by the helicopter, relative movement with contact between the rope and the highline could occur for various reasons. This could cause friction damage to the Highline. Furthermore, the contact between the highline and the longline could affect the control behavior of the helicopter. In the worst case, the longline needs to be released (in this case, see 2.1)

Mitigation:
- Abrasion-resistant coating of line and backups
- Line construction with multiple backups made of core-sheath ropes

Criticality with mitigation:
medium, as the sheath prevents friction damage to the line. Damage caused by hitting can be mitigated by the backups used. Dropping the rope does not cause the rescuer to fall

System:	Affected function:	Criticality:	Number:
rescuer	positioning (transl.)	high	3.3

Possible causes:
Highline gets between rescuer and patient or the rappel device on the longline gets caught in the highline

Description:
When the helicopter lifts the patient and rescuer, the highline can get between the patient and the rescuer. In this case, free departure is not possible even after cutting the leash (next phase). If the highline gets stuck on the rappel device in the longline, a complex load condition of the longline, leash, and other components occurs.

Mitigation:
- This situation can be easily prevented by creating a lateral distance of approximately one leash length between the rope and the highline before starting the lifting of patient and rescuer by the helicopter
- observer and patient intervene early by warning on the radio (air rescuer too low)
- If the situation cannot be resolved by the rescuer, the patient intervenes and lifts the highline above himself or the rescuer.

If the rappel system threatens to get caught on the highline, the patient pushes the rope and highline apart

Criticality with mitigation:
low, since it can be subsequently released by the flight rescuer or patient using a short leash (highline within grasping distance)

System:	Affected function:	Criticality:	Number:
rescuer	positioning (rot.)	high	3.4

Possible causes:
The rescuer and patient are in contact, the downwash from the helicopter causes them to twist and thus the longline and leash to twist. The rescuer does not take adequate action.

Description:
Even if the rescuer is not positioned too low below the patient, the leash and rope can become twisted. During the maneuver, the flight rescuer should prevent this to avoid an unwanted restraint situation of the helicopter.

Mitigation:
- By positioning the helicopter approximately one leash length in horizontal distance between line and longline, unwanted connections become apparent and twisting is prevented
- If there is no reaction from the rescuer, the patient grabs the highline and prevents twisting
- patient checks rope and highline for possible entanglement when lifting and warns early
- observer and patient intervene early via radio warning

Criticality with mitigation:
low, as the patient can intervene early and prevent twisting by grasping the highline.

The flight rescuer's "hooking the patient harness into the rope" function is no longer relevant in this and all subsequent phases. The function of "disconnecting the patient from the highline" must not be carried out in this phase, as otherwise, the pre-tension in the highline will generate a strong vertical oscillation that can lead to entanglement in the rope, patient, flight rescuer, or helicopter and must be avoided at all costs. If the flight rescuer initiates the next phase (cutting the leash) too early, the patient will intervene with an early warning.

Since cases 3.1 and 3.2 already deal with the release of the rope in this phase, it will not be explicitly listed again here.

System:	Affected function:	Criticality:	Number:
Highline	positioning	high	3.5

Possible causes:
Aerodynamic interaction of highline with helicopter downwash (rocking of the line in the wind)

Description:
By gradually relieving the load on the highline, the preload and thus the vibration behavior changes. This can cause the line to swing due to interaction with the downwash during lifting of patient and rescuer. This can occur even though no swinging was observed in the previous phases.

Mitigation:
- If the swinging is too strong: Lower the rescuer and patient to return to a stable situation and abort the rescue.
- Hand of rescuer on highline for guiding and manually dampening the vibration
- Short leash to ensure that the highline can be reached by the rescuer
- Sheathing of line and backup to prevent loops

Criticality with mitigation:
medium, as the formation of loops is prevented and the relief takes place gradually. This means that any swinging can be noticed early (haptically) and can be actively dampened to a certain extent by the arm of the rescuer. In the case of uncontrollable swinging, the highline can be loaded from the anchors to return to a stable state.

System:	Affected function:	Criticality:	Number:
Highline	load transfer	high	3.6

Possible causes:
Rockfall or other objects blown down by downwash

Description:
A falling stone, branch, carabiner, etc., is enough to cut the line under tension. As a result, the highline's load is suddenly transferred to the helicopter. This can lead to a high control load for the pilot.

Mitigation:
- Cleaning the anchors of loose stones and objects that could be thrown up
- Prohibit actions near the highline that involve throwing/kicking off objects/etc.
- Include pilot awareness/assessment

Criticality with mitigation:
medium. It is very unlikely that the anchors are cleaned sufficiently and the staff at the anchors behave accordingly. In addition, the pilot can be prepared

System:	Affected function:	Criticality:	Number:
Leash	load transfer	textcolorredhigh	3.7

Possible causes:
Fall of two people into the leash when releasing the longline

Description:
If the longline has to be released during this phase, the rescuer and patient will fall into the patient's leash. The highest fall load occurs at the highest point of the lifting process. This is the largest nominal load for the leash.

Mitigation:
- Avoid lifting above the zero line (unloaded highline). This can be easily detected by the rescuer due to the mobility of the leash ring
- Avoid sharp objects on harnesses/clothing of rescuer and patient
- Cutting tool for the leash cut remains secured in a holder
- No unprotected, sharp objects on patient and rescuer

Criticality with mitigation:
high, but can easily be avoided by taking measures (use of suitable clothing and harness and appropriate caution).

System:	Affected function:	Criticality:	Number:
harness	load transfer	medium	3.8

Possible causes:
Fall of two people in the leash when releasing the rope

Description:
If the rope has to be released in this phase, the rescuer and patient fall into the patient's leash. The rescuer's load path is via the longline into the belay loop of the patient's harness. The leash is usually tied parallel to the belay ring (threaded through the loops of the harness part and the leg part of the harness, as if directly tying in a climbing rope).

Mitigation:
As in phase 2: Hook the longline into the leash's attachment loop and the patient harness's attachment ring. If only one is possible, Hook it into the leash's attachment loop.

Criticality with mitigation:
low. It can be controlled very well through communication and the 4-eyes principle. However, a suitable communication channel is a prerequisite.

4.4 Phase 4: Cutting the Leash

This phase begins with a tool being used to cut the leash. Errors that arise from direct problems when cutting the leash are listed in the leash section of this chapter.

System:	Affected function:	Criticality:	Number:
helicopter	load transfer	high	4.1

Possible causes:
(Temporary) performance deficit of the helicopter

Description:
An unintentional loss of altitude during the cutting process of the leash can lead to an unintentional load on a leash that has already been cut. From this point on, the highline is no longer a fall protection device for rescuer and patient.

Mitigation:
- Leash shorter than arm length to ensure accessibility
- Stay in this phase as short as possible -> quick, safe cut
- patient with a second pair of scissors ready to help out if necessary
- Cut resistance of the sheath on the highline and the backups to prevent unwanted damage to theses systems
- The patient has a self-belay loop that can be hooked into the leash ring if necessary, and the highline functions as a safe fall protection device.
- Sufficient height under the highline for a fall with stretch of the highline by the weight of two persons
- Terrestrial rescue equipment and an easily accessible highline anchor
- Sufficient personnel with knowledge at the anchors for a terrestrial rescue

Criticality with mitigation:
high. A problem with the helicopter during this phase can have fatal consequences if it occurs unannounced. With a bit of time, a safe connection to the highline can be re-established

System:	Affected function:	Criticality:	Number:
helicopter	positioning	medium	4.2

Possible causes:
Tied-up helicopter steers the highline due to fluctuations in the hover position

Description:
The unloaded highline can easily be deflected in all directions. However, it swings back to its zero position after the leash is cut. This could cause it to get caught on the rescuer or patient

Mitigation:
- Abrasion-resistant coating of line and backups to avoid loops
- As little lateral deflection of the highline as possible when lifted by the helicopter

Criticality with mitigation:
medium. The sheath makes tangling less likely, and only one strand needs to be checked for entanglements.

The failure analysis of the harness in this phase is not discussed separately since no exceptional load case is known.

System:	Affected function:	Criticality:	Number:
rescuer	positioning (transl.)	high	4.3

Possible causes:
Flight rescuer and patient are close to the line, thus entanglement with the backup and highline is possible. The resulting situation might be unsafe and hard to solve.

Description:
Before cutting the leash, the patient and the flight rescuer should be approximately one leash length away from the highline (to the side). This makes it easy to see whether there is currently a second connection between the rescuer or the patient besides of the leash. If this is the case, this connection must be broken before cutting the leash. If the rescuer does not create such a distance by positioning the helicopter, the risk of becoming entangled after the cut of the leash increases.

Mitigation:
- This situation can be easily prevented by creating a lateral distance of approximately one leash length between the rope and the highline before starting to lift.
- observer and patient intervene early by giving a warning on the radio if no lateral distance has been created by the rescuer or if an unwanted second connection exists.
- If a second connection exists and cannot be released by the flight rescuer, the patient intervenes and releases the second connection in consultation with the flight rescuer (if possible).

Criticality with mitigation:
low, since the lateral distance to the highline provides a good overview of the existing connections and a pair of scissors for the patient and rescuer creates a large area in which unwanted connections can be cut.

System:	Affected function:	Criticality:	Number:
rescuer	positioning (rot.)	high	4.4

Possible causes:
Downwash can twist rescuer and patient, which can result in a tied-up situation even after a cut of the leash (friction of the leash on the rope due to wrapping)

Description:
If the leash is twisted or caught in the rappel device of the variable longline, the helicopter is tied up even after the leash has been cut. These connections can be difficult or even impossible to release due to tension.

Mitigation:
- By positioning the helicopter approximately one leash length in horizontal distance between line and longline the visibility of unwanted connections is increased, and twisting is effectively prevented
- If there is no reaction from the rescuer, the patient grabs the highline and prevents twisting (the leash length is adjusted accordingly)
- observer and patient intervene early via radio warning

Criticality with mitigation:
low, as the patient can intervene early and prevent twisting by grasping the highline.

System:	Affected function:	Criticality:	Number:
rescuer	dissolving the connection Patient with Highline	high	4.5

Possible causes:
The flight rescuer cuts the leash before all other (unwanted) connections of the patient to the highline are cut.

Description:
For example, by looping a highline backup around the patient's foot, the helicopter would remain tied up. Furthermore, this connection could be complicated to release after the leash has been cut

Mitigation:
- By positioning the helicopter approximately one leash length horizontally between the line and the longline, the visibility of unwanted connections is increased.
- patient and observer check whether patient, rescuer or rope have unwanted connections before rescuer reaches for the scissors
- observer and patient intervene early via radio warning

Criticality with mitigation:
medium, as 6 eyes check for unwanted connections. At the same time, this phase of the rescue process should be deliberately kept short. This requires early start of the check by patient and observer and rapid warning.

System:	Affected function:	Criticality:	Number:
longline	load transfer	high	4.6

Possible causes:
Helicopter has to release rope

Description:
If the leash has been cut, releasing the rope without warning would be fatal.

Mitigation:
- Leash shorter than arm length
- patient/rescuer can grab line with arm.
- patient/rescuer has self-belay loop ready for emergency
- patient/rescuer has a stable communication connection to the helicopter
- There is enough time to attach a safe connection to the highline

Criticality with mitigation:
high. Depending on the warning time, this still represents a critical moment. Whether a fuse can be attached depends on the warning time available.

System:	Affected function:	Criticality:	Number:
Highline	positioning	high	4.7

Possible causes:
Aerodynamic interaction of highline with helicopter downwash (swinging of the line in the wind)

Description:
If the highline swings due to the downwash when unloaded, the rescuer cannot manually dampen it because he needs his hands to cut the leash. This swing can interfere with cutting or make it very difficult.

Mitigation:
- patient dampens the highline manually if necessary
- Helicopter can create a slight lateral tension in the highline to keep rescuer and patient out of the range of movement of the swinging highline.
- Short leash to ensure that the highline can be reached by the rescuer
- Sheathing of line and backup to prevent loops

Criticality with mitigation:
medium, as loop formation is prevented. patient can manually dampen line. It is also possible to change the position of the helicopter sideways to the line until the leash is in slight tension.

System:	Affected function:	Criticality:	Number:
Highline	load transfer	low	4.8

Possible causes:
Rockfall or other objects blown down by downwash

Description:
A falling stone, branch, carabiner, etc., is enough to cut the line under tension. In this phase, the highline is no longer the load-bearing system. This means that it is less susceptible to breaking through. The breaking of the highline, which is no longer load-bearing, is not considered to have any influence.

Mitigation:
- Cleaning the anchors of loose stones and objects that could be thrown up
- Prohibit actions near the highline that involve throwing/kicking off objects/etc.

Criticality with mitigation:
low. Very unlikely if the anchors are cleaned sufficiently and the staff at the anchors behave accordingly. In addition, the load transfer to the helicopter longline is completed in this phase.

System:	Affected function:	Criticality:	Number:
Leash	load transfer	high	4.9

Possible causes:
Anything that can cause delays when cutting the leash, e.g., the scissors falling down, poor cutting performance, adverse conditions when cutting, etc.

Description:
In this phase, the “load transfer” function of the leash is deliberately destroyed by cutting

Mitigation:
- Only start the cutting process when the conditions allow for a quick cut
- Only use a simple leash that can be cut easily
- Second pair of scissors ready for patient. Good communication in case the cut goes wrong
- If problems persist, attaching of a sling to between the patient’s harness and the leash ring

Criticality with mitigation:
high. With two people ready to cut + good communication, -> a good opportunity to keep this process safe and short.

4.5 Phase 5: Departure

After completing Phase 4, the load-bearing path is limited to the heli, rope, and harnesses alone. In general, the operations in this phase are considered equivalent to a climber rescue.
For the sake of completeness, however, it should be mentioned again that backup loops, if present, can be inadvertently wrapped around the extremities or equipment of the rescuer and patient. This is a critical case due to the potentially tricky dissolution and the resulting consequences. In this analysis, however, a sheathing of the line and the backups is planned. This means that this difficult-to-control danger can be eliminated from the actual scenario for an exercise.

5 Modified highline setup for training

The usual structure of a highline already results in a very high safety standard. As described in Chapter 3, each component's simple redundancy is sufficient for normal use. Nevertheless, for the special case of the planned exercise scenario, we propose a special structure that deviates from the usual structure by adding additional safety components to exclude or minimize the safety concerns already discussed as best as possible.
For the special protection of the line and the backup, these are threaded through a 9m long fire hose, positioned in the middle of the line in the area of the patient. In addition to solid abrasion protection in the event of contact between the rope/air rescuer and the line, the hose also protects against falling parts, e.g., in the event of the
In addition, the loops of the non-tensioned, redundant backup ropes are covered, which prevents entanglement in these loops as best as possible.
To cope with the potentially greater forces acting on the entire system than in normal cases (2 people in the line; in the worst case, dynamic fall of two people including the rope into the line; lateral deflection by helicopter), the anchor points are set up with sufficient safety reserves. Instead of three 10mm bolts, four 12mm bolts are used at the western anchor point, and a compensating anchor is set up on four healthy trees (trunk diameter approx. 30cm) at the eastern anchor point. A solid, certified highline fabric is mainline (probably RedTube, Slacktivity, minimal breaking strength 36.9kN). For double redundancy in the event of a mainline failure, the backup system uses two separate core-sheath ropes. In addition to sufficient strength, these offer a higher level of safety in the event of cutting-edge loads from stones at the anchor point or sharp-edged material from the air rescuer/patient.

Instead of just one leash ring as a connection between the leash and the line/backup, two tested leash rings are used to ensure redundancy in the improbable event of a material failure of one ring.
To secure the patient on the line, only one strand of new climbing rope is used instead of a regular leash (climbing rope threaded into a hose band). The movable hose band above the rope makes cutting the leash much more difficult. It carries the risk of the safety not being wholly severed, which creates the very critical situation of the helicopter being tied up without a secure connection between the flight rescuer/patient and the line in the event of the rope being released. Using a single climbing rope makes the situation comparable to a climber's rescue from a rope.

6 Resulting procedure for training

Based on the error analysis, some positions in the procedure that should be expanded to increase the safety of those involved during the exercise can be identified. The assumed procedure from Chapter 2 is repeated below. Further coordination/elaboration with pilots and air rescuers, and further adjustments are explicitly desired.

rescue phase	special feature during exercise	rescuer tasks	patient tasks	observer tasks
0. Preparation	• Testing the radio connection • willingness of all officials • Material is to ensure	• test radio connection • test leash knots • check scissors available	• test radio connection • accessibility of the Highline by hand while hanging • Self-belay loop available and long enough • cutting scissors available and easily accessible	• test radio connection • unobstructed view on rescue operations • patient countercheck
1. Approach and positioning of the helicopter with rescue device and longline on rope	patient and observer grab if wrong approach or other error cases	Abseilcheck variables Rope, helicopter guidance, patient embracing, rope hygiene between rope, highline and leash	readiness signal, check approach	readiness signal, check approach
2. Hanging the patient in a cross-cut loop, the leash is shorter than usual, the backup loop Highline is not fixed,	Secure attachment of the patient harness in a longline. Rope hygiene between rope, highline, and leash	Check if the longline is correctly in your harness hung, ensure that the phases are adhered to, and warn FR in case of errors. If not released, intervenes by flight rescuer	Monitored helicopter position relative to Highline, Warns in case of errors, gives external assessment about termination	

3. Lifting by helicopter to the highline is relieved (load transfer)	Highline has no fixed backup loops in the exercise scenario	Know helicopter one to relieve the Highline and produce a horizontal distance from one leash length to the highline. Check whether there are any unplanned connections with the highline. Completed lifting by helicopter when the highline reaches its neutral position. Dampen any swinging up the Highline manually	Check for any unplanned connections with the Highline. Ensure to comply with the phases and warn FR in case of errors.	Monitored helicopter position relative to the highline, checked whether unplanned connections with the Highline passed, warned in case of mistakes, gave external assessment about termination
4. Cutting the leash (connection of climbing harness to highline	The structure of the leash is modified to include short residence time in this phase. After cutting, the connection can be reestablished using a self-belay loop on the patient (if the highline is accessible). In case of failure/loss of a pair of scissors, the patient is also covered by an equipped	Disconnects the patient harness from the highline in the neutral position of the highline. Check before cutting to see whether an unwanted connection or rescue equipment is caught on the highline.	Monitors whether FR only cuts the leash at the neutral point of the highline. Check before cutting whether there is an unwanted connection or rescue equipment attached to the highline. Holds a second pair of scissors and self-protection ready	Monitors whether FR only cuts the leash at the neutral point of the highline. Check before cutting whether there is an unwanted connection or rescue equipment attached to the highline.
5. Departure	No	Know helicopter a, regulated departure from station	no	no