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# Stabilization Environment for Swing Stabilization and MEDEVAC Hoists

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**This paper presents data related to helicopter sling load stabilization and MEDEVAC (Medical Evacuation) rescues collected by cadets performing research in the field at the United States Military Academy (West Point, NY) and Sapienza University of Rome (Rome, Italy) since 2018. The aim of this paper is to identify engineering constraints in MEDEVAC rescues. Constraints in two typical scenarios are presented. This information can then be included in simulations and models of swing stabilization and hoist control methods. Information is obtained through a literature review and interviews with U.S. Army helicopter pilots and crew chiefs who perform MEDEVAC rescues.**

## I. Nomenclature

| | | |
|---|---|---|
| KIAS | = | knots-indicated air speed |
| MEDEVAC | = | medical evacuation by helicopter; helicopter used in this situation |
| N | = | Newtons |
| rpm | = | revolutions per minute |
| SAR | = | search and rescue |
| SOP | = | standard operating procedure |

## II. Introduction

According to the 2013 National Search and Rescue (SAR) Academy Training Manual [1], the first helicopter rescue occurred in April, 1944, in Burma [2]. Lt Carter Harman of the U.S. Army Air Force flew an experimental Sikorsky YR-4 helicopter to rescue three British soldiers and one American airman, one at a time, flying each of the ten miles to

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another aircraft [2]. Lt Harman graduated from Princeton University in 1940 where he studied music composition. The first civilian helicopter rescue "was performed by Dimitry 'Jimmy' Viner, on November 29, 1945" in which two men were rescued from an oil barge with a "Sikorsky production model R-5 helicopter" [1]. As of 2015, the survival rate for casualties is about 90 percent [3]. However favorable that a 90 percent survival rate may seem, it fails to account for the shortcomings that are currently prevalent in MEDEVAC operations due to sling load instability.

Sling loads and MEDEVAC rescues have been described since the 1970s as an action which conducts medical evacuation procedures and techniques. The goal of stabilizing the rescue helicopter's slung loads is to improve the safety of both the aircraft crew and the evacuated personnel. This will increase the success rates of MEDEVAC operations and codify a safer solution than is used today [4–12].

A typical MEDEVAC rescue with a UH-60 Black Hawk is described by a U.S. Army pilot in Table 1. According to this interview, a typical MEDEVAC rescue is executed at 100-200 feet above the area and, typically, 100 feet of cable are used. A typical rescue takes no more than five minutes, and the cable speed to reel down and reel up is 200 feet per minute [13].

| **MEDEVAC Rescue discussion with CPT Medeiros. June 26, 2020 [13].** |
|---|
| Apaches do not conduct MEDEVAC rescues, so the following is all pertaining to rescues executed in the UH-60 Blackhawk. |
| In a typical MEDEVAC rescue, after the area is secured and the MEDEVAC aircraft are "cleared" in to pick up the patients, the pilot will typically execute an approach to a high hover (100-200 feet), while the crew simultaneously lowers the medic down in the hoist. The goal of the MEDEVAC crew during this process is to lower the hoist at such a rate as to allow the medic to reach the ground at the same moment in time as the helicopter stabilizes at the hover height that it will maintain for the rescue. During this phase, rotor wash is less of a factor because a skilled medic will be able to self-stabilize and prevent spin, to a certain extent, on his/her way down, by retracting or extending his/her arms. |
| Once the medic reaches the ground, he or she will connect the patient to the hoist cable, either in a litter (unconscious patient) or by a sling or harness underneath the patient's arms (conscious patient). The greatest risk of spin occurs in the litter patient. |
| Once the patient and the medic are connected back to the hoist cable, the MEDEVAC crew will begin to reel the cable back in. The cable in a UH-60 has 294 use-able feet, of which at least 100 are typically used. If the threat in the area is successfully neutralized, the crew will reel the patient in before the helicopter accelerates forward. At this stage, it is critical for the MEDEVAC rescue crew to observe the litter. If it begins spinning, they stop reeling the cable in, which usually stops the spinning. At this stage, there is rotor wash, but because there is no forward movement, there is little risk of the rotor wash inducing a spin that cannot be stopped by changing the speed of the cable reeling in. The rotor wash acts on the load uniformly all the way up. |
| If there is significant enemy threat in the area, the pilots may have to begin to accelerate forward as the load is ascending, which significantly increases the risk of spin. This is because the main factor that initiates the spinning load is the load passing through the rotor wash unevenly, which occurs until the aircraft passes through 16-24 knots in forward flight. After that, the rotor wash is aft of the aircraft and no longer a factor on the load. If a load in forward flight is spinning too severely to stop by the reel alone, the pilots may have to slow down or adjust flight profile to allow the load to stabilize. |
| The entire rescue process should take no more than 5 minutes. The cable can be extended or reeled in at up to 200 feet/minute. As far as spin rate, the spin can get up to hundreds of RPMs if the rescue is done incorrectly, but the crew makes every effort to prevent spin from occurring. I would say maximum spin rate of the load observed during a well-executed rescue should not exceed 1 or 2 rpm, basically nothing more than a slow, single rotation or two as the litter ascends toward the aircraft. |
| As to your last question, the Apache would not conduct any sort of evacuation except in the most dire of situations. The apache only has two seats for pilots and no additional crew, so the only way an apache could evacuate another service member is with the service member sitting on the lateral wings, ideally with a strap anchoring them to the apache transmission mount. Ideally this would only ever be done with a conscious patient. |

**Table 1 CPT Medeiros discusses MEDEVAC Rescues [13].**

Several models have been proposed for the control problem such as containers and slung loads [4, 5, 14–19]. However, the sling loads commonly analyzed in these works are large objects, commonly referred to as high-mass sling loads. These high-mass sling loads and container control solutions are not applicable to low-mass sling loads as the kinematics of the problem affect the loads in much different ways. Currently, a commercial approach to stabilizing swing has recently been introduced by a company called Vita Inclinata.[20] This is a "processor-controlled litter using a pair of ducted fans" [21] for MEDEVAC operations that appears to use counterbalancing weights that dampen oscillations and rotation.[20]

MEDEVAC loads require retrieval of individuals, so the sling load is an individual on a hoist that is drawn to the helicopter. At any point in the hoisting process, external and internal inputs such as pilot control inputs and wind loads could affect the stability of the load. If these oscillations are too large, the load could be cut, which is a common course of action for high mass, cargo loads. Since cutting the load in the case of a MEDEVAC would mean the loss of life, it is not feasible for MEDEVAC hoists, and it is therefore much more dangerous for the aircraft and the crew [22–29].

Methods for stabilization of sling loads and hoists include studies of the dynamics of container cranes and are an active area of research in academia [15–19, 30–37] and industry [20, 38–40]. Currently, for MEDEVAC rescues, the common solution to solving this oscillation is the crew chief of the aircraft grabbing the sling and attempting to stabilize it themselves. This is an extremely dangerous maneuver as it endangers the safety of the crew chief. Constantly fighting the cable's oscillation can lead to the crew chief pulling a muscle or even being pulled out of the aircraft if not fastened to the air frame properly. This method is also contingent on the crew noticing these oscillations. If a crew member does not observe the swinging load, the cable could strike the helicopter, resulting in essentially a pulse input into the controls, likely resulting in a crash if the pilot cannot recover properly. Additionally, in severe oscillation conditions, the hoist's contact with the frame could create a serrated edge, resulting in the sling being cut. For these reasons, there is a need for a reliable sling load stabilization system that can effectively dampen low mass, lightly damped sling load oscillations demonstrated in 2019 by Morock *et al.* [41].

## III. Mission

The difference between slung cargo loads and hoisted MEDEVAC casualty evacuations are not only different in their payloads, but also in the environments that they are connected to a helicopter. When connecting sling loads of freight or fuel, military personnel have ample time to carefully inspect and emplace the connection points of the cargo to the helicopter. In the case of a hoisted MEDEVAC rescue, time is not a resource that can be wasted for two factors. The first being that in a medical evacuation, there is the presence of an individual who needs medical attention. A common goal for rescue teams is to take combat casualties to their nearest aid station within an hour; they call this hour "The golden hour" [42]. In order for a helicopter to move to a casualty collection point and then transport the casualty to an aid station, speed is often the highest priority. The only factor which supersedes the need for speed is safety. This need for safety is why grounded MEDEVAC operations, where the helicopter briefly lands to load casualties, is often preferred to hoisted MEDEVAC operations. A landed helicopter is a more stable platform for medical personnel to strap down casualties who may have sustained complex head or neck trauma during an engagement. Also, a landed helicopter is also a more beneficial environment to stabilize a casualty before lifting off again. However, this preference for landed MEDEVAC helicopters is something that enemy combatants have realized. A tactic that recently occurred is to engage with friendly forces and create severe enough casualties to mandate a UH-60 Blackhawk to be called in. Once friendly casualties are created, the enemy will disengage and wait for the much larger and susceptible medical helicopter to land. Once landed, it is far easier for the enemy to reengage, and they now have the ability to damage not only friendly personnel but also a friendly medical helicopter. Therefore, although a grounded helicopter is the preferred option for MEDEVAC rescues, in today's battlefield hoisted MEDEVAC operations save more lives and time. However, this preference is predicated on the ability for MEDEVAC crews to reel in casualties safely and efficiently with respect to time and stability. Thus, a solution to create safe and efficient MEDEVAC sling loads is required in order to continue to save lives.

## IV. Sling loads and MEDEVAC hoists

Table 2 outlines different constraints for applicable aircraft [43]. The CH-47 Chinook, UH-60 Black Hawk, and the MEDEVAC hoist used on these aircraft all have varying constraints on their respective payload weights. Since MEDEVAC operations are typically conducted using UH-60, the load is subjected to the kinematics of this helicopter in motion. Table 3 highlights these constraints [44].

| Physical Constraints of Various Sling Loads [43] | | | |
|---|---|---|---|
| **Constraint** | **Black Hawk** | **Chinook** | **MEDEVAC Hoist** |
| Weight capacity | 8-9,000 lbs | 26,000 lbs | 600 lbs on “slow”; 300 lbs on “fast” |
| Speed with sling load | < 120 KIAS | 60 KIAS | Variable |
| Rate of hoist | - | 1000 feet/minute | Slow: 0-125 feet/minute; Fast: 0-250 feet/minute |

**Table 2 Physical Constraints of Various Sling Loads [43]. The “aircraft weight capacities are from the underslung cargo hook which doesn’t reel-in or out.”[21]**

Hoist operational constraints and kinematics of UH-60 Black Hawk are shown in Table 3. There is a 60° maximum angle for sling loads as this is the angle at which the rope will strike the bottom of the aircraft [45]. Additionally, there is a 30° bank angle for the aircraft that cannot be exceeded [45]. In a “hot zone,” or area where the helicopter is under fire, it is highly favorable for the individual to be hoisted within 90 seconds [46]. As such, this can be taken into account as a “worst case scenario.”

| Hoist Operational Constraints and Kinematics of UH-60 Black Hawk [44] | | |
|---|---|---|
| **Constraint Type** | **Constraint** | **Value** |
| Hoist | Maximum weight<br>Usable cable length.<br>Cable winding speed<br>(“fast”, “slow”) | 2668.9 N<br>88.4 m<br>(1.778, 0.0508) $\frac{m}{s}$ |
| UH-60 Helicopter | Maximum acceleration<br>(forward, rear, side, down, upward)<br>Acceleration time to maximum velocity<br>(forward, rear, side, down)<br>Maximum velocity<br>(forward, rear, side, down, upward | (7.3, 9.0, 11.6, 1.7, 3.0) $\frac{m}{s^2}$<br>(7, 2, 2, 3) s<br><br>(51.4, 18.0, 23.2, 5.1, 8.2) $\frac{m}{s}$ |
| Wind | Wind speed (Disturbance force) | Est. 5.0 $\frac{m}{s}$ (20 N) |

**Table 3 Hoist Operational Constraints and Kinematics of UH-60 Black Hawk [44].**

In interviews with helicopter pilots, the maximum speed of a helicopter with a suspended casualty and various physical constraints related to the hoist cable and speed were obtained as shown in Table 4 [47–49]. This table provides values for the maximum helicopter velocity, maximum cable length, crew chief role, tag line, hoist angle, hoist reeling speed, cable length, and sensor location (for cable). Values of the hoist distance, extraction time, reel out and reel in time, and time to reduce swing before extraction in a typical MEDEVAC rescue are also shown in the table. The actual hoist point of the helicopter is located 6 feet above the sensor that measures the oscillations of the sling load.

The current Standard Operating Procedure (SOP) for the U.S. Army requires the use of taglines to prevent MEDEVAC casualties placed inside litter from spinning [11]. Figure 1 outlines the preferred, acceptable, and least desirable placement of tag lines (These are Figs. E-3A, B, C on pp. E-18 and E-19 of [11]). These lines aid in the stabilization of the MEDEVAC sling load but are only helpful as long as a soldier has taken hold of the tag line. Once the line runs out of available slack, the load will begin oscillating. This method therefore would be inapplicable to environments where personnel would be unable to stand up and control a tag line. This example therefore exhibits the need for a more consistent method for stabilization.

Table 5 provides a table of constraints for the hoist and crew of a UH-60 [47–49]. Constraints provided include the maximum hoist angle, desired hoist angle, value for a bad (undesired) angle, hoist angle without the use of a crew chief’s hand, and hoist angle with the use of a crew chief’s hand. The table also shows the value for the maximum cable length and an estimated cable length during hoist operations.

Table 6 provides a table of constraints for crew chief and typical MEDEVAC rescue [47–49]. The table explains that the hands of the crew chief are always on the cable during MEDEVAC operations to maintain control of the suspended

| Constraints for the Hoist and Crew of the UH-60 [47–49] | | |
|---|---|---|
| **Constraint Type** | **Constraint** | **Value** |
| Maximum Helicopter Velocity | Suspended casualty | 100 knots |
| Maximum Cable Length | Actual Maximum on Hoist | 240 feet |
| | Estimated cable used during Operations | 100 feet |
| Crew Chief | Hands of the Crew Chief are always on the cable during MEDEVAC operations | Maintain control of the suspended casualty. |
| | | Attempt to eliminate bird nesting within the cable. |
| | | Attempt swing out the cable connection point to the casualty to minimize the amount of minute helicopter position adjustments. |
| | | Crew chief has gloves on. |
| | | Crew chief adjusts hoist speed with thumb (rheostat). |
| Tag line | Secondary tag line | There is usually a secondary tag line attached to the casualty on the ground to limit rotation. |
| Hoist Angle | Maximum angle | 15 degrees in any direction. |
| | Desired angle | 2 to 5 degrees. |
| Hoist Reeling Speed | Cable length > 20 feet | 100 feet/minute. |
| | Cable length < 20 feet | 75 feet/minute. |
| Typical MEDEVAC rescue | Hoist distance | 20 feet |
| | Time to lower medic | 16 seconds |
| | Reel out and reel in (Maximum) | 45 seconds |
| | Time to reduce swing before extraction | 45 - 16 seconds = 29 seconds |
| Sensor location | The sensor that measures the hoist length is six feet below the hoist. | Add six feet to the measured cable length to obtain the actual cable length from the hoist. |
| Cable length | The actual hoist point of the helicopter is 6 ft above the sensor that measures the oscillations of the sling load. | The actual cable length is the sum of the measured cable length and the height difference between the hoist point and the sensor. |

**Table 4 Constraints for the Hoist and Crew of the UH-60 [47–49].**

casualty. The relative position of the crew chief's hand is approximately three feet below the hoist point in an MH-60M and approximate four feet below the hoist point in an MH-47G. The crew chief has gloves on and adjusts the hoist speed with the thumb. This table notes that in a typical MEDEVAC rescue, the hoist distance is 20 feet; the time to lower the medic is 16 seconds; the total reel out and reel in time is 45 seconds; the time to reduce swing before extraction including extraction, is approximately 29 seconds. Table 7 provides a table with constraints on the Breeze-Eastern hoist [21].

| Constraints for the Hoist and Crew of the UH-60 [47–49] | | |
|---|---|---|
| **Constraint Type** | **Constraint** | **Value** |
| Maximum Velocity | Suspended casualty | 100 knots |
| Maximum Cable Length | Actual Maximum on Hoist | 240 feet |
| | Estimated cable used During Operations | 100 feet |
| Tag line | Secondary tag line | There is usually a secondary tag line attached to the casualty on the ground to limit rotation. |
| Hoist Angle | Maximum angle | 15 degrees in any direction |
| | Desired angle | 2 to 5 degrees |
| | Bad angle | Probably lower than 15-20 degrees |
| | Without crew chief's hand | about 5 degrees |
| | With crew chief's hand | up to 10 degrees |
| Hoist Reeling Speed | Cable length > 20 feet | 100 feet/minute |
| | Cable length < 20 feet | 75 feet/minute |

**Table 5 Constraints for the Hoist and Crew of the UH-60 [47–49].**

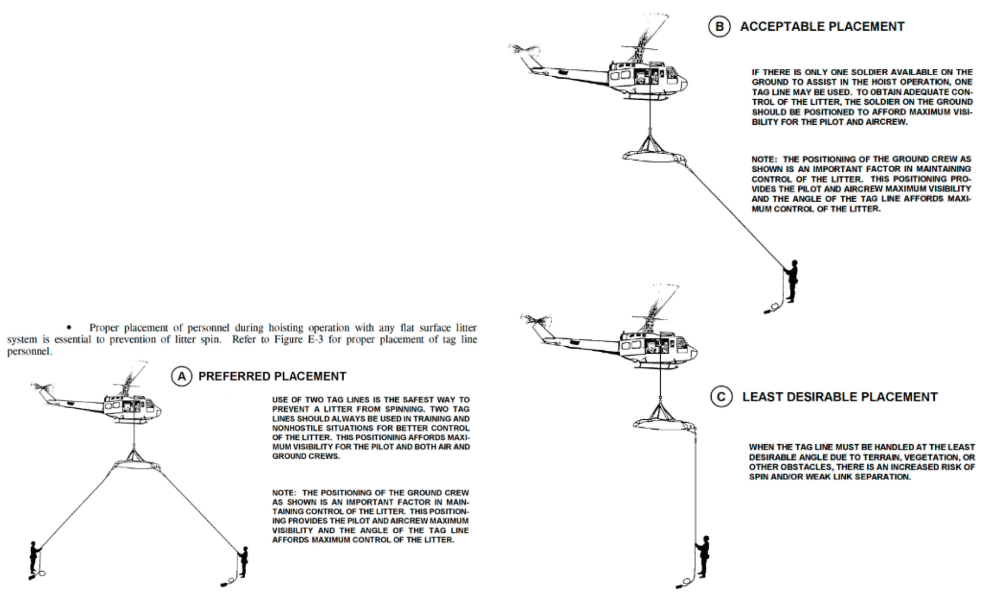


**Fig. 1 U.S. Army Preferred Placement of Tag Lines (Figs. E-3A, B, C on pp. E-18 and E-19) [11]**

.

## V. Brief review of cadet research in swing load stabilization

In 2019, Morock *et al.* in collaboration with Sapienza University of Rome (Rome, Italy) demonstrate that oscillations of a pendulum can be stabilized with the use of time-delayed feedback of the pivot point that translates horizontally along the direction of the helicopter [41]. This research models the suspended individual as a 299-kg point particle that is elastically suspended from the translating pivot point of a helicopter that is in a steady hover. A genetic-like algorithm is adopted to help the simulations incorporate the values of the optimal control parameters. The results showed that an individual suspended at the bottom of a cable with an initial length of 88-meters and released from rest at an initial swing angle of 1 degree was retrieved to within 1 meter of the helicopter in 90 seconds using a cable speed of 1.778 meters per second for the first 85 meters and a cable speed of 0.0508 meters per second for the final two meters; the

| **Constraints for the Hoist and Crew of the UH-60 [47–49]** | | |
|---|---|---|
| **Constraint Type** | **Constraint** | **Value** |
| Crew Chief | Hands of the Crew Chief are always on the cable during MEDEVAC operations | Maintain control of the suspended casualty. |
| | | Attempt to eliminate bird nesting within the cable. |
| | | The crew chief's hand position is roughly 3 feet below the hoist in a MH-60M and roughly 4 feet below the hoist in a MH-47G. |
| | | This measurement varies from Soldier to Soldier, and from hoist (maneuver) to hoist. |
| | | Though for simplicity, these measurements would represent the average. |
| | | Attempt to swing out the cable connection point to the casualty to minimize the amount of minute helicopter position adjustments. |
| | | Crew chief has gloves on. |
| | | Crew chief adjusts hoist speed with thumb (rheostat). |
| Typical MEDEVAC rescue | Hoist distance | 20 feet |
| | Time to lower medic | 16 seconds |
| | Reel out and reel in (Maximum) | 45 seconds |
| | Time to reduce swing before extraction | 45 - 16 seconds = 29 seconds |
| | Time to stabilize the cable and extract | 29 seconds |

**Table 6 Constraints for the Hoist and Crew of the UH-60 [47–49].**

cable was stopped at a distance of 1 meter below the hoist point. A wind disturbance during the entire hoist phase was modeled as as a constant force of 20 N that corresponds to a wind speed of 5 meters per second [43].

In 2020, Aldhizer and Morock *et al.* demonstrate proof of concept that the swing angle and cable length can decrease simultaneously during a hoisting phase through the use of pulse pairs that change the cable length at appropriate choice of swing angles [50–52]. This research changed the cable length using a constant speed (up and down). The aim of this research was to create an algorithm that could limit the displacement angle of a suspended individual below a helicopter by changing the relative length of the cable at different points within the swing of the slung mass.

In 2021, Morock *et al.* in collaboration with Sapienza University of Rome (Rome, Italy) demonstrate that oscillations of a pendulum can be stabilized with the use of a variable length sling load and hoisting control method that raises the cable at the ends of the swing (that is, at the points in time when the suspended individual reaches the maximum swing angle in the swing) and lowers the cable at the middle of the swing (that is, at the points in time when the suspended individual reaches the vertical line) and is otherwise free swinging [53]. This approach is an active variable length control strategy that models the suspended individual as a point particle rigidly suspended from a stationary pivot point. The motion of the suspended individual is described by a fully nonlinear dynamic model and is simulated using time integration of the nonlinear equations of motion. A genetic-like algorithm is also adopted to obtain values of the optimal control parameters. Simulations of a MEDEVAC rescue focused specifically on the hoist phase of an individual suspended initially at a distance of 32 meters below the helicopter and swinging with an initial angle of 15 degrees is found to be both stabilized to a final swing angle of 5 degrees and hoisted to a final distance of 1.8 meters (that is, at the bottom of the helicopter) in 300 seconds using a hoist speed (up and down) of 0.501 meters per second [53].

| Constraints on Breeze-Eastern hoist. [21] | |
|---|---|
| Hoist maximum speeds | up to 350 fpm |
| Maximum cable length | 290 feet |
| Hoist speed for cable length < 12 feet (from hoist aperture) | 100 fpm |
| Maximum hoist angle | "30 degrees from centerline, or a 60-degree cone"[21] |
| Sensor location | On the hoist |
| Weight capacity | 600 lbs at top speed[21] |

**Table 7 Constraints on Breeze-Eastern hoist.[21] The "aircraft weight capacities are from the underslung cargo hook which doesn't reel-in or out."[21]**

# VI. Two MEDEVAC scenarios

In this section, constraints for two MEDEVAC scenarios are presented. The first subsection discusses constraints in the most common MEDEVAC rescue. The second subsection discusses constraints in a MEDEVAC rescue from a hot zone.

We start by introducing some parameters used in this section to describe the constraints. The actual initial length of the cable, $l_0$, is obtained by adding the measured hoist length, $l_h$ of the cable by the sensor at the bottom of the helicopter to the distance to the sensor, $l_s = 6$ feet, between the hoist and the bottom of the helicopter. The expression for $l_0$ can be written as

$$l_0 = l_h + l_s, \quad (1)$$
$$= l_h + 6 \text{ feet}, \quad (2)$$
$$= l_h + 1.8288 \text{ meters}. \quad (3)$$

The distance $l_s$ between the sensor at the bottom of the helicopter and the hoist is approximately 6 feet.

In the stabilization phase of the rescue, the swing angle of the cable oscillation must be reduced to a angle suitable for extraction, $\theta_e$, before reducing the cable length. The extraction angle is given by

$$\theta_e = 5 \text{ deg}. \quad (4)$$

As soon as the swing angle is reduced to the extraction angle $\theta_e = 5$ deg, then the hoisting phase of the rescue can begin.

At the point in time when the patient is moved into the helicopter, the final length of the cable is

$$l_f = 6 \text{ feet}, \quad (5)$$
$$= 1.8288 \text{ meters}. \quad (6)$$

The patient can be loaded into the helicopter when the cable length takes on a value that is its final length, $l_f$, and the swing angle takes on a value that is less than the extraction angle, $\theta_e$.

## A. Most common MEDEVAC rescue scenario

In this subsection, we discuss parameters in the most common MEDEVAC rescue. Table 8 shows a summary of parameters for the most common MEDEVAC rescue scenario (see also Tables 5 and 6). Table 9 shows parameters in the portion of a MEDEVAC rescue for retrieving a patient upward to the helicopter in the most typical scenario (values are obtained from Tables 5, 6, and 8).

In this scenario, the total time, $t_{typ}$, for the typical MEDEVAC rescue is to be less than or equal to the total time for both the stabilization and the hoist phase $t_s$ and the time to lower the medic, $t_m$. Taking the sum of these contributions, we obtain

$$t \leq t_{typ}, \quad (7)$$

where

$$t_{typ} = t_s + t_m, \quad (8)$$
$$= 29 \text{ sec} + 16 \text{ sec}, \quad (9)$$
$$= 45 \text{ sec}. \quad (10)$$

| **Summary of parameters for most common MEDEVAC rescue scenario (see also Tables 5 and 6)** |
|---|
| Initial cable length, $l_0$ = 20 feet + 6 feet = 7.9248 meters |
| Initial angle, $\theta_0$ = 15 degrees “in any direction” |
| Time to reduce swing to 5 degrees before extraction, including extraction, $t_s$ = 29 seconds (29 sec = 45 sec - 16 sec) |
| Breeze-Eastern hoist speed, $v_s$ = 75 feet per minute = 0.381 meters per second (for cable lengths less than 20 feet) |

**Table 8 Summary of parameters for most common MEDEVAC rescue scenario (see also Tables 5 and 6)**

| **Parameters in portion of rescue retrieving patient upward to helicopter in most typical scenario (see also Tables 5, 6, and 8)** | |
|---|---|
| start time, $t_0$ | 0 sec |
| stop time, $t_s$ | 29 sec |
| start length, $l_0$ | 7.9248 meters |
| end length, $l_f$ | 1.9288 meters |
| initial angle, $\theta_0 = \theta_e$ | ≤ 15 deg “in any direction” |
| end angle, $\theta_f$ | ≤ 5 deg |
| vertical speed, $v_s$ | 0.381 m/s |

**Table 9 Portion of rescue retrieving patient upward to helicopter in most common MEDEVAC scenario (see also Tables 5, 6, and 8)**

The hoist length, $l_h$, in the typical MEDEVAC cable rescue is given by

$$l_h = l_{typ}. \tag{11}$$

The initial typical measured length of the hoist is $l_h = l_{typ}$ from the sensor at the bottom of the helicopter, such that the initial length of the cable is $l_0$, given by

$$\begin{aligned} l_0 &= l_h + l_s, && (12)\\ &= t_{typ} + l_s, && (13)\\ &= 20 \text{ feet} + 6 \text{ feet}, && (14)\\ &= 7.9248 \text{ meters}. && (15) \end{aligned}$$

The initial swing angle, $\theta_0$, of the typical rescue can be taken to be as large as 15 degrees, namely

$$\theta_0 \leq 15 \text{ deg}. \tag{16}$$

The time to start the MEDEVAC rescue will be taken to be $t_0 = 0$ sec.

The time, $t_e$, to stabilize the swing angle to the suitable angle for extraction, $\theta_e$, is given as

$$t_s = 29 \text{ sec}. \tag{17}$$

The vertical speed of the cable during the stabilization phase, where the cable length is less than $l_0$, can be taken to be

$$\begin{aligned} v_s &= 75 \text{ feet/sec}, && (18)\\ &= 0.381 \text{ m/s}. && (19) \end{aligned}$$

In the hoisting phase of the rescue, the swing angle must be maintained less than $\theta_e$ while the cable length is reduced to the final length $l_f$. The final length of the cable is

$$\begin{aligned} l_f &= 6 \text{ feet}, && (20)\\ &= 1.8288 \text{ m}. && (21) \end{aligned}$$

| Summary of parameters for longest cable MEDEVAC rescue in hot zone (see also Table 5) |
|---|
| Initial cable length, $l_0$ = 100 feet + 6 feet ≈ 32.3 meters |
| Initial angle, $\theta_0$ = 5 degrees |
| Worst angle, $\theta_w$ = 15 degrees "in any direction" |
| Extraction time in hot zone, $t_{hz}$ = 90 seconds [46] |
| Breeze-Eastern hoist speed, $v_f$ = 100 feet per minute = 0.508 meters per second (for cable lengths greater than 20 feet) |
| Breeze-Eastern hoist speed, $v_s$ = 75 feet per minute = 0.381 meters per second (for cable lengths less than 20 feet) |

**Table 10 Summary of parameters for longest cable MEDEVAC rescue in hot zone (see also Table 5)**

The vertical speed of the cable during the hoisting phase, where the cable length is less than $l_0$, can also be taken to be the smaller of the two hoist speeds $v_s$, such that

$$\begin{aligned} v_s &= 75 \text{ feet/sec}, && (22)\\ &= 0.381 \text{ m/s}. && (23)\end{aligned}$$

**B. Longest cable MEDEVAC rescue in hot zone**

In this subsection, we discuss parameters in the MEDEVAC rescues using the longest cable length in a hot zone [46]. Table 10 shows a summary of parameters for the longest cable rescue in a hot zone. Table 11 shows parameters in the portion of a MEDEVAC rescue for retrieving a patient upward to the helicopter in the longest cable rescue in a hot zone.

In this scenario, the total time, $t_t$ for the MEDEVAC rescue in a hot zone is to be less than or equal to the time, $t_{hot}$ for both the stabilization and the hoist phase, such that

$$t \le t_{hot}, \tag{24}$$

where

$$t_{hot} = 90 \text{ sec}. \tag{25}$$

The hoist length, $l_h$, in the MEDEVAC rescue in the hot zone is given by

$$l_h = l_{hot}. \tag{26}$$

The initial typical measured length of the hoist is $l_h = l_{hot}$ from the sensor at the bottom of the helicopter, such that the initial length of the cable is $l_0$, given by

$$\begin{aligned} l_0 &= l_h + l_s, && (27)\\ &= l_{hot} + l_s, && (28)\\ &= 100 \text{ feet} + 6 \text{ feet}, && (29)\\ &\approx 32.3 \text{ meters}. && (30)\end{aligned}$$

The initial swing angle, $\theta_0$, of the MEDEVAC rescue in the hot zone can be as large as 15 deg in any direction,

$$\theta_0 \le 15 \text{ deg}. \tag{31}$$

As in the previous scenario, the time to start the MEDEVAC rescue will be taken to be $t_0 = 0$ sec.

The time to conduct the rescue in the hot zone, $t_h$, including stabilization and hoisting, is 90 sec, such that

$$t_h = 90 \text{ sec}. \tag{32}$$

The vertical speed of the cable during the stabilization phase, as long as the cable has length is longer than 7.9248 meters, is taken to be

$$\begin{aligned} v_l &= 100 \text{ feet/sec}, && (33)\\ &= 0.508 \text{ m/s}. && (34)\end{aligned}$$

| **Parameters in portion of rescue retrieving patient upward to helicopter for scenario with longest cable MEDEVAC rescue in hot zone to lower the cable and raise the cable) (see also Tables 5 and 10)** | |
|---|---|
| start time (lower cable from hoist), $t_0$ | 0 sec |
| time to lower cable (from helicopter), $\Delta t_{\text{lower}}$ | $0.381(7.92 - 1.93) + 0.501(32.3 - 7.92) \approx$ 14.5 sec |
| time to raise cable (back up to helicopter), $\Delta t_{\text{raise}}$ | 90 sec - 14.5 sec $\approx$ 75.5 sec |
| stop time (load patient into helicopter), $t_f = t_{hz}$ | 90 sec |
| start length (at helicopter), $l_0$ | 1.93 meters |
| longest cable (start hoist upward), $l_s$ | 32.3 meters |
| end length (load patient into helicopter), $l_f$ | 1.93 meters |
| start angle (at helicopter), $\theta_0$ | $\leq 5$ deg |
| worst angle (start hoist upward), $\theta_w$ | $\leq 15$ deg |
| end angle (load patient), $\theta_f$ | $\leq 5$ deg |
| vertical speed when cable length < 20 feet, $v_s$ | 0.381 m/s |
| vertical speed when cable length > 20 feet, $v_f$ | 0.501 m/s |

**Table 11 Portion of rescue retrieving patient upward to helicopter in MEDEVAC rescue in hot zone (see also Tables 5 and 10)**

In the hoisting phase, when the cable length is shorter than 1.8288 meters, then the vertical speed of the cable can be taken to be

$$v_s = 75 \text{ feet/sec}, \tag{35}$$
$$= 0.381 \text{ m/s}. \tag{36}$$

In the hoisting phase, the swing angle must be maintained less than $\theta_e$ while the cable length is reduced to the final length $l_f$.

# VII. Summary

This paper describes the stabilization environment in which a MEDEVAC rescue occurs and provides quantitative estimates of constraints involved in a rescue. These constraints and quantitative values will allow the cataloging of necessary information in order to promote and streamline future research in this area. Prior work has articulated a vision for future progress, and this paper's findings from real world MEDEVAC pilots and subject matter experts will allow further research to be grounded even more precisely in actual applications and constraints in this area. The focus on transitioning from the theoretical possibility of stabilizing slung loads and MEDEVAC hoists, to quantifiably applying these methods, will save lives and revolutionize the way that helicopter sling loads are managed.

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