Comparison of Fall Forces between Fixed-Point and Redirected Belays in Rock and Ice Climbing Systems

Derek DeBruin
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Abstract

Difficult climbing on steep terrain immediately above the belay anchor creates significant hazard for climbing parties. When other methods are impractical, parties may choose between a fixed-point belay on the anchor and a more traditional redirected belay from the belayer's body. In three test cases, forces on the anchor, climber, and belayer were explored to compare and contrast fixed-point and redirected belays. The results suggest that while force on the anchor is comparable between fixed-point and redirected belays for small falls, force on the climber increases with the fixed-point belay, while reducing force on the belayer. Consequently, a belay device such as a munter hitch that facilitates rope slip and attendant energy absorption due to friction is required. This keeps force on the climber within acceptable limits (<=6kN). The author concludes by outlining the advantages and disadvantages of various belay strategies for such consequential terrain.

Introduction

Multipitch climbs present the significant hazard of factor-2 falls, which occur if the leader falls on a pitch prior to placing any protection above the belay anchor. This hazard can sometimes be mitigated with a "chariot belay"—tethering the belayer a significant distance below the anchor, thereby putting more rope into the system and reducing the fall factor. Unfortunately, this solution requires a significant amount of rope and creates complication in protecting the follower while disassembling the anchor when it is their turn to climb. The leader might also clip a high piece above the anchor and lower or downclimb back to the anchor stance to solve this problem. Such a solution is not always practical, depending on the available protection and the pitch length (and therefore rope available). Many climbers will clip a component or the masterpoint of an anchor as the first piece of protection. Unfortunately, this creates the problem of load multiplication on the anchor. Further, in any high-factor fall, the belayer is at considerable risk of injury as such falls are quite violent and may move the belayer with significant force.

One solution to this problem is to employ a "fixed-point" or "direct anchor" belay, wherein the leader is belayed directly off the anchor, as opposed to off the belayer's body (harness). This helps isolate the belayer from the force of the fall, reducing the force on the belayer and subsequent risk of injury. This also decreases the likelihood the belayer will drop the leader due to the reduced risk of injury. However, a direct high-factor fall onto the anchor raises questions regarding the security of the anchor and impact force on the falling lead climber, particularly if the belayer's mass is removed from the fall-arrest system.

Presently available data suggest that fixed-point belays and body belays result in comparable forces on the anchor (Bedogni, n.d. and Batoux, 2017) for fall factors less than 2. The relative similarity in forces on the anchor, belayer, climber, and top piece of protection do not provide strong support for either belay method relative to the other for lower fall factors. Some testing has been conducted with factor-2 or other high-factor falls (Bedogni & Manes, 2011, Bertolani, 2009, and Club Alpino Italiano 2014). However, much of the publicly available information is in Italian. Using the fixed-point belay as a method for protecting the leader remains an open question among a largely English speaking American audience.

Experimental Set-Up

Three test cases were conducted using the drop tower at the Petzl Technical Institute in Salt Lake City, Utah. Tests were conducted using soft 80kg masses constructed of haul bags loaded with hand weights and climbing ropes. Masses were constructed with weighted limb simulators made of coiled ropes to better model a human climber. All test cases were designed to determine the effects of high-factor falls, where a leader has not yet placed protection and falls directly onto the belay. Due to differing rope lengths in the respective systems, test cases explored lead falls from the same position on a simulated route (relative to the belay anchor), rather than employing the exact same fall factor.

The first test case was an attended belay system, with the belay device located on the belay mass. The belay rope was redirected through a single component of the anchor and then tied to the climber mass with a bowline. A bowline was selected for the climber mass to facilitate ease of untying and resetting between tests. This bowline was tied by the same individual for each test and hand tightened. The belay rope was adjusted to eliminate slack but provide no tension. The belay anchor was comprised of two bolts equipped with hangers for rock climbing placed in a horizontal configuration. The belayer mass was attached to the masterpoint of a "ponytail" anchor created by the bight of an overhand knot tied in a 120cm nylon sling clipped to the two bolts. Load cells were applied at the climber mass, belayer mass, and redirect point on the anchor to record maximum forces.

The second test case was a fixed-point belay system rigged with a "banshee belay" anchor (Coley, 2014). The belay anchor was comprised of two bolts equipped with hangers for rock climbing placed in a horizontal configuration. The rigging included a double-loop bight knot (to create the "fixed point") on one end of a 120cm HMPE sling attached to one bolt, backed up with a clove hitch tied in the sling on the second bolt. The belayer mass was attached to the fixed point. A munter hitch secured with an overhand slip hitch was also attached to the fixed point, with the belay rope running directly to the climber mass and tied to the climber mass with a bowline. The belay rope was adjusted to eliminate slack but provide no tension. Load cells were applied at the climber mass and the belay point on the anchor to record maximum force.

In both of these cases, the belayer mass was suspended by a figure 8 knot on the mass to a clove hitch on the anchor, with 30cm of rope between the top of the figure 8 knot and the base of the clove hitch. This distance was elected as it simulates a reasonable arm's length distance from the anchor that a belayer might typically select at a belay stance on steep terrain. In the case of the redirected belay, this resulted in a distance of approximately 1m from the belayer mass to the redirect bolt.

The belay device used in the first two test cases was a munter hitch secured with a hand-tightened overhand slip hitch. This choice of belay device eliminates much of the rope slip in the system and was selected to minimize variability and provide direct comparison between these test cases. In both cases, the belay rope was a used 10.1mm Sterling rope that had not been subject to lead falls. Five tests were conducted for each test case, all on the same end of the rope. Rope ends were switched between test cases. The climber mass bowline tie-in knot and the munter-slip hitch belay knot were both untied and re-tied to hand tightness between tests.

In both of these cases, the climber mass was raised by winch and suspended 1.2m above the bolts of the anchor. The mass was disconnected from the winch via pull cord on a quick-release shackle, causing free fall of approximately 2.4m until caught by the belay. In the redirected body belay test case, there was approximately 1.6m of rope in the system (fall factor 1.5). In the fixed-point test case, there was approximately 1.2m of rope in the system (fall factor 2).

The third test case used a fixed-point belay and was similar in nearly all respects to the second test case. This test case was designed to test the effects of rope slipping through a belay device, particularly the munter hitch. A climber mass was suspended 1.2m above a fixed anchor point. The climber mass was tied with a bowline (by the same individual as test cases one and two). The rope was run through a munter hitch on the fixed point and then to an alpine butterfly knot 0.9m beyond the munter hitch (length selected based on the "inertial phase" of belaying as described in Bedogni, n.d.). A 20kg semi-rigid mass was suspended on a quick-release cord was affixed to the alpine butterfly knot. Ropes for the third test case included used 9.8mm Sterling ropes for the first six drop tests and new 10.3mm Petzl ropes for the final two drop tests. Ropes were changed between each test case to minimize the effect of rope fatigue between tests.

The 20kg mass on the brake strand of the munter hitch was used to simulate a belayer's hand and arm. The test site and attendant risk to the belayer's hand was not conducive to using a live belayer for these tests. Consequently, typical belayer grip strength was measured by having belayers maintain a brake hand as increasing load was applied on the opposite side of a munter hitch. The force required to move a belayer's hand or allow rope to slip through the belayer's hand was recorded. Braking force provided by a belayer's grip generally ranged from 0.2kN to 0.25kN. Consequently, a

20kg mass was used to simulate the "inertial phase" of belaying (Bedogni, n.d.). This would necessarily eliminate any potential for rope slippage at the belayer's hand (the "slipping phase"), but would allow for rope slippage through the munter hitch and minimize variability between tests. The 0.2kN value used is in keeping with other research into belayer grip strength (Braun-Elwert, 2006; Stronge & Thomas, 2013; Titt, 2017). The simulated belay relied only on the inertial phase of belaying and not on the slipping phase. Further, the retarding force of the braking mass necessarily changed with its upward acceleration. Consequently, real-world forces in the third test case are likely lower than reported here.

As all test cases were designed to test for the same fall location relative to the anchor, and not for the same fall factor, results could provide a practical directive for a preferred belay method in the case of a leader fall prior to placing protection.

Results

Test Case 1: Redirected Body Belay

Results for the redirected body belay are detailed in Table 1 below, with the experimental set up detailed in Figures 2 and 5 below. As expected, anchor loads increased with successive drops as the rope was not changed between tests (though knots were loosened and re-tied). The force recorded on the anchor was roughly equal to the sum of the force on the climber and the belayer, though slightly lower than expected. The test apparatus was such that on many tests the falling climber mass grazed the ground, which could explain the difference. Also of note, during each test the belayer mass was completely displaced from its position until striking the redirect carabiner, at times rebounding to its original position. On the final test, the sheath of the rope ruptured completely near the munter hitch, likely owing to catching on a sharp edge on the carabiner auto-lock gate as the carabiner rotated into a cross-loaded position during this test.

Test Case 2: Fixed-Point Belay

Results for the fixed-point belay are detailed in Table 2 below, with the experimental set up detailed in Figures 3 and 5 below. As expected for the direct belay from the anchor, force on the anchor is equivalent to force on the climber, with forces on the anchor similar to those on the redirected body belay. Though the existing literature often cites lower forces on the anchor with the fixed-point belay, these were not observed, likely due to the lack of rope slip occurring at the belay (addressed in test case three below). On the third test, friction from the rope slip that occurred was sufficient to expose the rope core at the climber tie-in and the munter hitch. New rope sections were used to complete the final two tests.

Test Case 3: Fixed-Point with Rope Slip

Results for the fixed-point belay with rope slipping through a munter hitched are detailed in Table 3 below, with the experimental set up detailed in Figures 4 and 6 below. The first test in this case was a replication of the second test case as the testing rig was moved. This test revealed comparable results to those of the prior test case. The subsequent tests revealed a sizeable reduction in force owing to rope slipping through the munter hitch. In many cases rope slip induced damage to the rope, typically glazing of the sheath, but also some core damage. Figure 1 shows representative examples of this damage.

Figure 1: Representatives samples of rope damage—glazing (left) and core exposure (right).

Table 1: Redirected Body Belay

#	Anchor Force (kN)	Climber Force (kN)	Belayer Force (kN)	Notes
1	7.2	4.2	3.2	
2	7.8	4.8	3.5	
3	8.2	4.7	3.7	Rope abraded at redirect carabiner.
4	8.2	5.1	3.7	
5	8.6	5.0	3.8	Sheath fully ruptured; core strands intact.
$\bar{x}$	**8.0**	**4.76**	**3.58**	

Table 2: Fixed-Point Belay

#	Anchor Force (kN)	Climber Force (kN)	Notes
1	7.2	7.0	
2	8.6	8.3	
3	8.1	8.0	Rope core shot at climber tie-in and munter; new rope end cut.
4	7.3	7.3	Rope sheath glazed at munter hitch.
5	8.5	8.5	
$\bar{x}$	**7.94**	**7.82**	

Table 3: Fixed-Point with Rope Slip

#	Climber Force (kN)	Notes
1	7.74	Calibration test; similar to test case 2. Some sheath melt, small amount of core exposed.
2	6.06	Sheath destruction, small core shot.
3	5.66	Minor glazing.
4	4.06	Glazing, some core damage (flattened rope).
5	5.88	
6	5.80	
7	4.90	Minor sheath damage.
8	7.50	Significant core shot; rope snagged on carabiner gate.
$\bar{x}$	**5.39**	*excludes tests 1 and 8

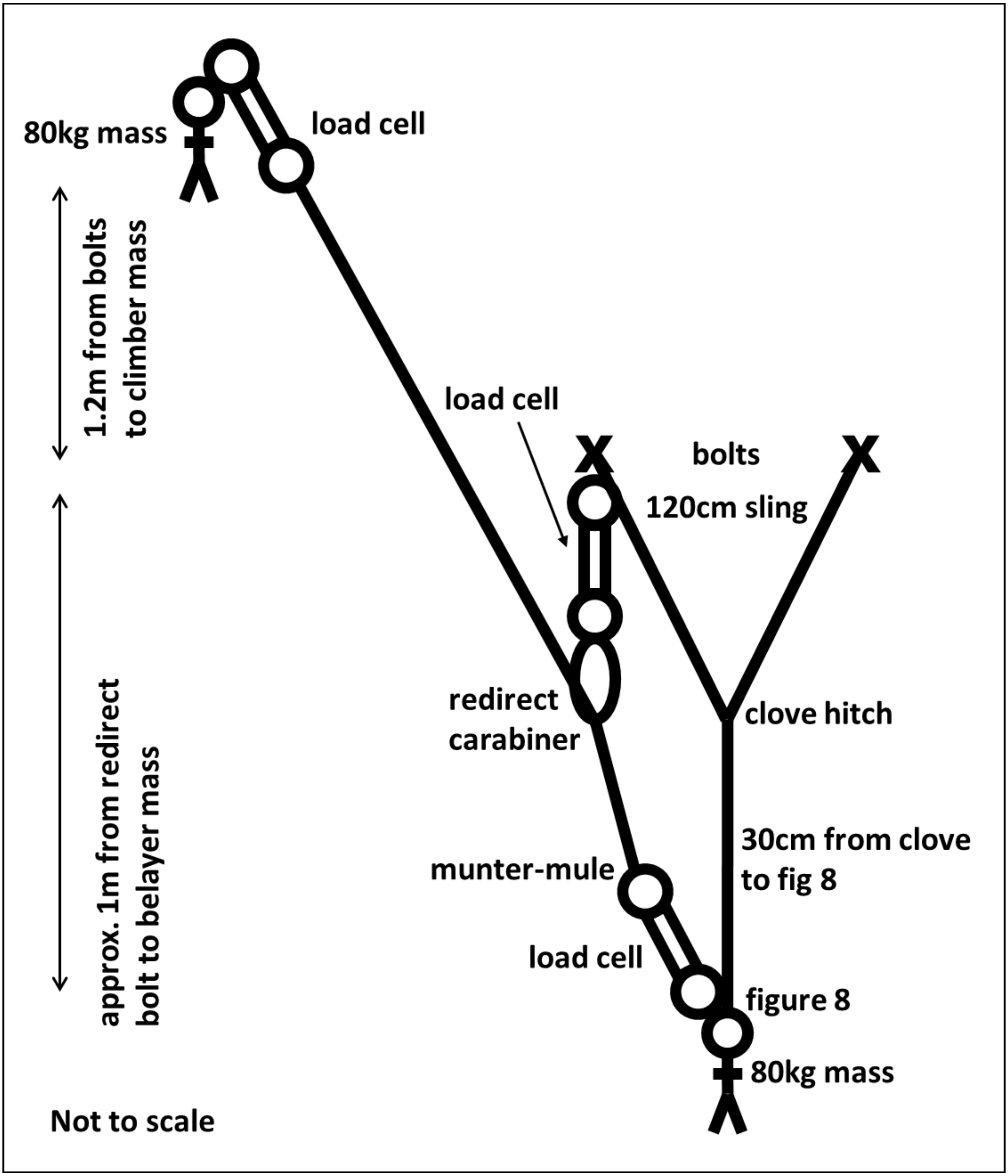

Figure 2: Redirected Body Belay

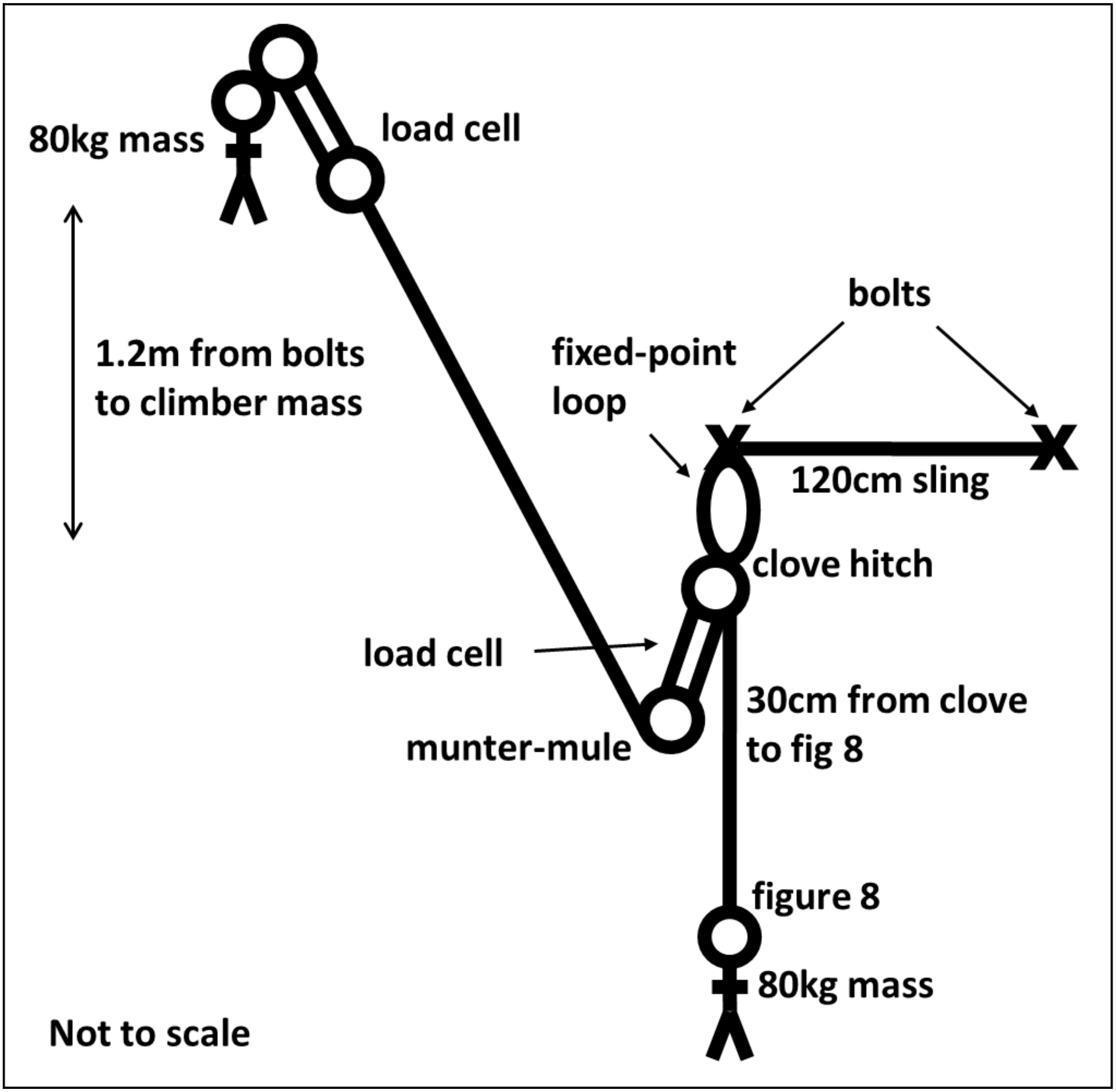

Figure 3: Fixed-Point Belay

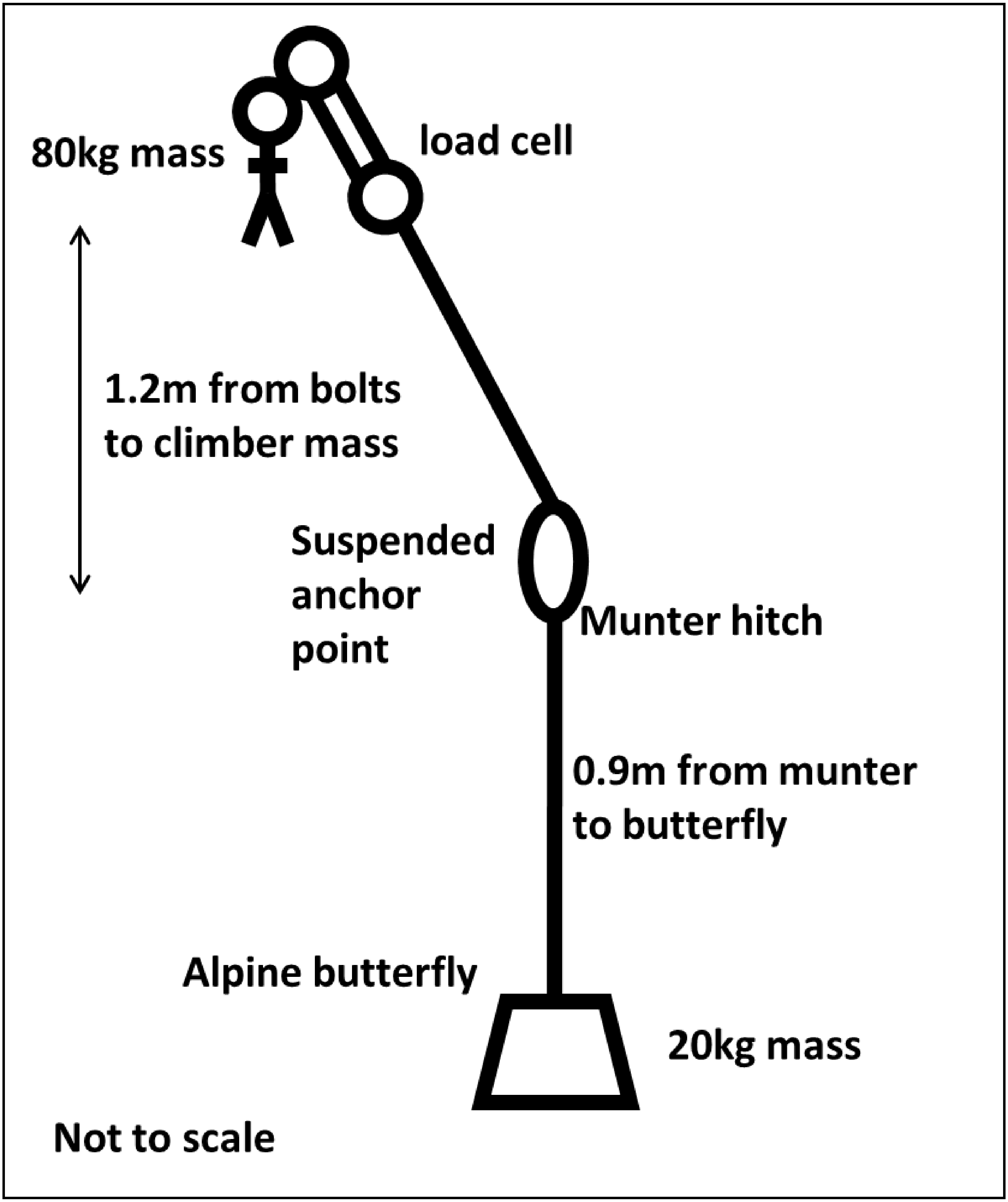

Figure 4: Fixed-Point with Rope Slip

Figure 5: Test cases 1 and 2 set-up, belayer mass and anchor (left) and climber mass suspended from above (right).


Figure 6: Set up for test case 3; climber mass (left) and brake strand mass (right).

Discussion

As the test cases involve a small number of relatively imprecise samples, any comparisons and attendant conclusions cannot be considered definitive. However, the data allow for broad inferences regarding the relative merits of a redirected belay from the belayer's body versus a fixed-point belay.

A redirected belay and fixed-point belay produce similar loads on the anchor if the leader falls a short distance prior to placing protection. The 8kN loads produced in this testing are severe enough to call into question the integrity of the anchor components as 8kN is enough force to damage or destroy some climbing protection, questionable rock, or suspect ice. Such a severe load reflects the similarly high peak forces based on theoretical calculations in which rope slip and attendant friction at the belay device are ignored (many such calculators are available online of various quality, largely based on the underlying physics described in Goldstone, 2006). Bedogni & Manes found similarly high forces in their 2011 testing. However, as test cases 1 and 2 were conducted with munters with slip hitches, introduction of rope slip and friction in test case 3 reduces the loads to more manageable forces in the 5kN to 6kN range.

A redirect on the belay anchor splits the resulting force between the climber and the belayer, with a larger portion of the force affecting the climber. Previous research demonstrates the ratio of force on the climber to be roughly twice that of the belayer for fall factor 1 (Petzl America n.d. a). The tests presented here resulted in force on the climber approximately 1.4 times that of the belayer, which may reflect differences in the fall factor (approx. FF1.5) as well as friction. However, the conclusion is the same: there is adequate force on the belayer to move the belayer quite severely in the case of a high factor falls (>=1) (Petzl America n.d. a). Forces of 3kn to 4kN are more than enough to displace an 80kg belayer by 1m or more, which could easily result in serious injury to the belayer. Forces on the climber of 4kN or more would be similarly unpleasant. Additionally, forces greater than approximately 2.5kN may be sufficient to cause uncontrolled slippage of rope through the belay device, and may compromise the braking assistance function of geometry-based assisted braking devices, such as the Mammut Smart, Edelrid MegaJul, etc. (Titt, 2017).

As the forces on the anchor are similar for the small fall tested, a fixed-point belay has the advantage of sparing the belayer. This is particularly important for the lead climber as the belay may be rendered ineffective if the belayer is incapacitated due to injury, a real possibility given the forces in a redirected belay. Unfortunately, the significant drawback of the fixed-point belay is that the climber bears the full force of the fall. In the case of a belay system with minimal rope slip (such as the munter-slip hitch knot of test cases 1 and 2), the force is unacceptably high (7kN to 8kN). Standardized industrial fall protection systems used in North America limit peak forces to 8kN (American National Standards Institute, Inc., 2016) as this minimizes significant injury to a human (though the experience of such a force may still be quite unpleasant). In the European Union, average forces must not exceed 6kN (OSHWiki, 2017).

Rope slipping through a belay device results in a significant amount of energy absorption due to friction, as shown between test cases 2 and 3, as well as prior testing (Petzl America n.d. b). Comparing test cases 2 and 3 directly may overstate the energy absorption by a small amount as new ropes or rope ends were used for each evolution in test case 3. However, a reduction in force on the climber of at least 2kN (instead of the 2.6kN indicated in Tables 2 and 3) is a reasonable assumption, particularly given the limitations of the simulated brake hand in test case 3. Most importantly, this energy absorption resulted in a reduced force on the climber, bringing the peak force to the 5kN range, below the 6kN threshold. Forces on the climber may be further reduced by rope slip at the belayer's hand (in addition to slip at the belay device as tested here), though this will vary among belayers. Reduction in force may also come from real braking not modeled by the accelerating mass used in test case 3. A small amount of belayer displacement is also possible depending on the particular anchor rigging with a fixed-point belay, which could further affect force on the climber.

Comparing the redirected belay and the fixed-point belay, the fixed-point belay places minimal force on the belayer but results in approximately 0.75kN additional force on the climber in these tests. This remains below the recommended 6kN, but additional force is not ideal. However, the additional protection afforded to the belayer and the attendant security of the belay may justify this tradeoff. Regardless, rope slip at the belay device is recommended to prevent catastrophically high forces to the anchor and climber. For this reason, belay devices which minimize rope slip—including a host of assisted braking devices such as the GriGri—are not advised for fixed-point belaying unless otherwise indicated by the manufacturer (Petzl America n.d. c).

The redirected belay reduces the force on the climber at the cost of significant belayer displacement. However, the redirect point creates a “pulley effect,” resulting in force multiplication at the redirect point. Note that test case 1 had an approximate fall factor of 1.5 while test case 2 had an approximate fall factor of 2, yet the force on the anchor was roughly equivalent. In falls of greater length (and therefore greater fall factor for the redirected belay), this force multiplication becomes more significant and could produce forces great enough to call into question the security or strength of the components of the anchor. Consequently, if the lead climber anticipates progressing a distance of greater than 1m to 1.5m before placing the first protection, the anchor should be unquestionably strong or a fixed-point belay may be preferable to reduce forces on the anchor.

Unfortunately, none of this changes the severity of a high-factor fall immediately above the anchor prior to placing the first piece of protection. Rope damage is a real possibility in the event of a fall. Regardless of the belay method selected, the leader may be forced to select from a number of unsavory options. Consequently, there are times when the old adage of, “The leader must not fall,” may still apply.

Recommendations

When faced with the prospect of difficult climbing on steep terrain directly off the anchor, the climbing team generally has four options:

1. A “chariot belay” where the belayer is tethered well below the anchor, to put more rope into the belay system.
2. Clipping the first piece of protection on the subsequent pitch and downclimbing or lowering, so that the lead climber already has protection other than the anchor when starting the next pitch.
3. A “fixed-point” or “direct anchor” belay employing a munter hitch on a compatibly shaped (HMS) carabiner, as described above.
4. A belay on the belayer’s harness redirected through a point on the anchor.

Each of these options has advantages and disadvantages, outlined in Table 4 below. There are a number of practical resources available discussing the rigging for these systems. For examples, see Association of Canadian Mountain Guides, 2012; École Nationale de Ski et d’Alpinisme, 2017; Edelrid Gmbh & CO., 2012; Coley, 2014a; Coley, 2014b; Houston, 2005; and Semmel, 2012.

The chariot belay puts more rope in the system, reducing the fall factor. It also allows for greater belayer displacement with less risk of impact than other methods. However, unless using double ropes, the belayer might be required to manage their own security over a potentially long distance when following the pitch; the top belay may only be effective once the belayer has climbed up to the anchor, depending on the tethering method selected. The chariot belay also eliminates a potentially large quantity of rope that may be needed on the subsequent pitch.

Clipping protection on the subsequent pitch above the anchor provides immediate protection to the lead climber. However, this may not always be possible—there may not be enough rope available or the leader may not have the correct gear available to protect the start of the following pitch. The leader will also need to lower or downclimb back to the anchor, and depending on who leads the next pitch, the transition to the next lead becomes more complex. Depending on the fall consequences, the leader may also be disinclined to climb through difficult moves at the end of a pitch, particularly if rope stretch and/or poor communication are concerns.

A fixed-point belay minimizes hazard to the belayer without increasing force on the anchor (relative to a redirected belay). This can protect belayers from impact hazards (such as an overhead roof, a sharp pull into the wall, etc.), particularly lighter/smaller belayers. Protecting the belayer also increases the likelihood a high-factor fall will be caught, a real concern in such violent falls. Unfortunately, this significantly increases the force on the climber, mandating the use of a belay method that permits significant rope slip (such as a munter hitch). This removes the additional security afforded by an assisted braking device and demands greater belayer control of the rope; gloves are advisable.

A redirected belay will be familiar to most climbers, but comes with significant consequence to the belayer in addition to those suffered by the climber. Regrettably, measures to resist belayer displacement, such as an upward-pull component attached to the belayer, simply increase the severity of the fall for the climber, akin to the fixed-point belay. Further, the pulley effect increases the load on the anchor even for relatively short falls, particularly if an assisted braking device is used.

The authors recommend that practitioners select a belay method based on the competence of the climbing party, the terrain at hand, and the protection options in light of the advantages and disadvantages outlined above. When possible, a chariot belay or pre-clipping protection on the subsequent pitch will offer greater security to the climbing party. When this is not possible, the party should carefully consider the relative merits of the fixed-point and redirected belay. Often a hybrid of options 3 and 4 works well—begin with a fixed-point belay until a few pieces of protection are established, then transition to a belay from the belayer's waist. If in doubt, retreat may be prudent.

Table 4: Comparison of Belay Methods

Method	Pros	Cons
Chariot belay	Potentially large reduction in fall factor	Uses lots of rope; can be challenging to protect the follower
Pre-clipped first piece	Reduces fall factor, removes force from anchor	May not have enough rope/gear, more complex transition, downclimb/lower required
Fixed-point belay	Minimizes belayer hazard, greater likelihood of holding fall	Cannot use ABD (unless using hybrid system), rope slip required or force on climber is increased
Redirected belay	Familiar, can use ABD	Significant hazard for both belayer and climber, greater force on anchor

Conclusion

When faced with difficult climbing on steep terrain directly off the anchor, climbing parties have a number of options to manage the hazard. When a chariot belay or pre-clipped first piece are not possible, the alternatives are a fixed-point belay or redirected belay. A redirected belay results in lower forces on the climber, but may result in large forces on the anchor due to the pulley effect. Belayer displacement and possible injury are also serious concerns. A fixed-point belay protects the belayer, but requires significant rope slip to prevent unacceptably large forces on the climber. If the party is unsure, retreat may be the best option.

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