Comparative Analysis of Typical Grab Knots Force Test in Rope Rescue

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Abstract. Fire rescue is all-weather and all-time. Using rope rescue technology to carry out rescue operations is one of the efficient and convenient methods adopted by firefighters. Grab knots are an important part of this field. This article introduces typical grab knots such as Prusik knot, French knot, Klemheist knot and uses 10.5mm and 12.5mm as main ropes, 6mm, 7mm and 8mm as auxiliary ropes and related equipments in rope rescue to carry out parallel tests by using tensile testing machine. It can be found that the larger the diameter of rope, the greater the maximum tensile force the grab knot will bear. The larger the diameter difference between the main rope and auxiliary rope, the smaller the sliding distance is, and the force effect can be better. Those three types of grab knots have different characteristics and should be selected according to the actual situation. Relatively speaking, the Prusik knot is more suitable for fire rescue. It is hoped that it will help to improve the firefighters' understanding of typical grab knots, and play a certain reference value for the safety assessment, so as to ensure the scientific and safety of rescue operations.

1. Introduction
Rope rescue technology is undoubtedly one of the most important rescue methods for firefighting teams. Grab knots are commonly used in rope rescue, usually for safety protection and braking, and their effect in rescue determine the level of the force limit of the entire rope system. The difference of the usage conditions, as well as the characteristics of typical grab knots, all have an impact on the force effect of the knots. Therefore, the force test analysis and comparisons of typical grab knots can provide a certain reference value for the safety assessment of firefighters.

1.1 Prusik knot
Prusik Knot, was invented by Dr Karl Prusik in the early 19th century[1]. It is mainly used for fall protection when climbing up or down along the rope. It is also often used in raising and lowering rope rescue system and has become an important part of pulley system. The advantages of prusik knots are simple and quick to make and not easy to slip off the main rope, good fixing effect, and two-way locking. The disadvantage is that it is difficult to release after being grasped by an external force, and it is generally difficult to move the prusik knot up and down along the main rope to adjust its position.
1.2 French knot
French knot (also called Autoblock), has a simple knotting method and is mostly used for falling protection[2]. Like the Prusik knot, the French knot can also be used in both directions on the main rope. The advantage of French knot is that it is easy to descend and protect, and it can be safely fixed when stressed. It can freely adjust and move up and down along the main rope when it is not stressed. The disadvantage is that the length of the grabbing loop is required. If the remaining loop is too Long, it is easy to lose its effect, and it is easy to slip when used for lifting, so as to cause the safety problem.

1.3 Klemheist knot
Klemheist knot, is derived from the French knot, which is similar to French knot[3]. This knot can only brake in one direction and is mainly used for protection and braking in rope rescue. The advantage of the Klemheist knot is that the length of the rope loop can be handled flexibly, its fixing effect is better, and it is easy to release after loading. The disadvantage is that the free movement of the Klemheist knot on the main rope is limited after being stressed.

2. Typical grab knots force tests
In order to better match the actual firefighting situation, this paper uses the tensile testing machine which is shown in Figure 2, to carry out the force test which are designed for different grab knots, different diameter ropes. The tests test the slip distances and force values of the grab knots under different variables, so as to compare the force effect of typical grab knots.

2.1 Test process
The main ropes commonly used in fire and rescue are 10.5mm and 12.5mm, and the auxiliary ropes are 6mm, 7mm and 8mm. Therefore, the test research is focused on the ropes with the above diameters and the rope brand is Beal. In the test, the main rope and auxiliary rope of different diameters are combined, and various knotting test items with different wraps are set. For example: 6mm P4+10.5mm represents the test of 4 wraps of Prusik knot made of 6mm auxiliary rope on 10.5mm main rope. The code of the Klemheist knot is K and the French knot is the code F. The grouping method is the same as that of the Prusik knot. The test is carried out on a horizontal tensile testing machine. The position of the grab knot is marked before and after the test, and the slip distance is measured with a ruler.

2.1.1 Prusik knot force test
Using the tensile testing machine, first fix and tie the 10.5mm main rope at one end of the testing machine, and then use the 6mm auxiliary rope to make 4 wraps of Prusik knot on the main rope and use the rope to connect with the carabiner to fix it on the other end. Mark the main rope at both ends of the Prusik knot. The process is expressed in Figure 4. Gradually increase the pulling force and observe the changes of the force of Prusik knot on the main rope until the grab knots fail to fall off or the rope is broken by force. Record the tensile force value at this time and the grasping force curve during the test. If a break occurs, measure and record the distance moved according to the marks made on the two ends of the grab knots on the main rope, and record the test data.

Increase the number of wraps of the knot to 6, and test again in the same way. Replace the auxiliary ropes and use other diameter auxiliary ropes to make Prusik knots. The force test is carried out according to the same test method, and the force effect of Prusik knot with different diameters and different
numbers of wraps on the 10.5mm main rope is obtained. Replace the main rope with 12.5mm, and use three kinds of auxiliary ropes to make Prusik knots and repeat the above test. Organize the data obtained from the test and record it in the table 1.

Table 1 Force test of Prusik knot

| Item         | Max tension (KN) | Slip distance (mm) | Failure sign          |
|--------------|------------------|--------------------|-----------------------|
| 6mm P4+10.5mm| 4.5924           | —                  | Continuous slip       |
| 6mm P6+10.5mm| 11.5542          | 24                 | Auxiliary rope break  |
| 7mm P4+10.5mm| 3.2822           | —                  | Continuous slip       |
| 7mm P6+10.5mm| 15.4631          | 81                 | Auxiliary rope break  |
| 8mm P4+10.5mm| 2.8500           | —                  | Continuous slip       |
| 8mm P6+10.5mm| 17.7263          | —                  | Main rope skin break  |
| 6mm P4+12.5mm| 12.3492          | 40                 | Auxiliary rope break  |
| 6mm P6+12.5mm| 13.0373          | 13                 | Auxiliary rope break  |
| 7mm P4+12.5mm| 15.5366          | 76                 | Auxiliary rope break  |
| 7mm P6+12.5mm| 15.2687          | 29                 | Auxiliary rope break  |
| 8mm P4+12.5mm| 6.8852           | —                  | Continuous slip       |
| 8mm P6+12.5mm| 23.5087          | —                  | Main rope skin break  |

2.1.2 Klemheist knot force test

The force test method of the Klemheist knot is similar to the Prusik knot force test. According to the way of knotting this knot, three kinds of diameters of auxiliary ropes are used to make 6 and 8 wraps Klemheist knots respectively. First carry out the force test on the 10.5mm main rope, record the relevant data, and then replace the main rope, and again carry out the force test on the Klemheist knots made with different diameter auxiliary ropes, and record the results in the following table 2.

Table 2 Force test of Klemheist knot

| Item         | Max tension (KN) | Slip distance (mm) | Failure sign          |
|--------------|------------------|--------------------|-----------------------|
| 6mm K6+10.5mm| 12.5841          | 195                | Auxiliary rope break  |
| 6mm K8+10.5mm| 11.4424          | 35                 | Auxiliary rope break  |
| 7mm K6+10.5mm| 13.5870          | 390                | Auxiliary rope break  |
| 7mm K8+10.5mm| 14.2987          | 257                | Auxiliary rope break  |
| 8mm K6+10.5mm| 16.9663          | —                  | Main rope skin break  |
| 8mm K8+10.5mm| 16.1602          | —                  | Main rope skin break  |
| 6mm K6+12.5mm| 14.5729          | 29                 | Auxiliary rope break  |
| 6mm K8+12.5mm| 13.5353          | 21                 | Auxiliary rope break  |
| 7mm K6+12.5mm| 15.5427          | 118                | Auxiliary rope break  |
| 7mm K8+12.5mm| 14.1912          | 35                 | Auxiliary rope break  |
| 8mm K6+12.5mm| 19.6540          | 390                | Auxiliary rope break  |
| 8mm K8+12.5mm| 21.2969          | 114                | Auxiliary rope break  |

2.1.3 French knot force test

When testing with French knot, a French knot with 6 wraps is made with 6mm auxiliary rope, and the main rope is 10.5mm. It is found that because the way of knotting French knot is special and easy to loose, this combination doesn’t work, so the slip distance cannot be measured. Change the number of the wraps of the knot to 8 and 10, and then measure the force effect of the same diameter auxiliary rope on the 10.5mm main rope. Replace the main rope to 12.5mm, and then use the above method to repeat the test and record the results in the table 3.

Table 3 Force test of French knot

| Item         | Max tension (KN) | Test situation |
|--------------|------------------|----------------|
| 6mm F6+10.5mm| 1.3347           | Continuous slip|
| 6mm F8+10.5mm| 14.0161          | Short plunge   |
| 6mm F10+10.5mm| 13.7907        | Short plunge   |
| 7mm F6+10.5mm| —                | Cannot grasp   |
2.2 Test analysis

2.2.1 Prusik knot force test analysis

In the test, it was found that the Prusik knot broke into two cases, one is the skin of the main rope is broken; the other is the rope loop is broken. It can be seen from the position of the break that the break positions occurred at the side which connected with the carabiner. The double fisherman knots did not break and loosen. On the contrary, as the tension increased, the friction between the main rope and the grab knots increased and high temperature was generated, the bond was very tight so that the rope should be scrapped and replaced.

From the test data, it can be seen that the 4 wraps of Prusik knots made of different diameter auxiliary ropes have different force performance on the same main rope. On the 10.5mm main rope, the 4 wraps of Prusik knot continued to slip regardless of the diameter of the auxiliary rope, and all failed. As shown in Figure 2, the 4 wraps of Prusik knot made of 6mm auxiliary rope, when the tension is greater than 4.5924KN, the Prusik knot will continue to slip and fail. On the 12.5mm main rope, due to the larger diameter of the main rope, the 4 wraps Prusik knot made of the 6mm and 7mm auxiliary ropes can hold the main rope firmly, and the slip distance is relatively small, 40mm and 76.8mm respectively. On the 12.5mm main rope, compare with the 4 wraps of Prusik knot made of 6mm and 7mm auxiliary ropes. The sliding distance of the 6mm rope is relatively small. It is shown that the diameter difference has an impact on the performance of the force.

| Diameter of Main Rope (mm) | Diameter of Auxiliary Rope (mm) | Test Force (KN) |
|---------------------------|-------------------------------|-----------------|
| 7                        | 8                             | 2.8300          |
| 7                        | 10                            | 3.3328          |
| 8                        | 6                             | Cannot grasp   |
| 8                        | 10                            | 2.1900          |
| 8                        | 6+12.5                        | 1.6687          |
| 6                        | 12.5                          | 1.1532          |
| 6+12.5                   |                               | 21.8033         |
| 6                        | 12.5                          | 24.7974         |
| 7                        | 12.5                          | 24.1279         |
| 7+12.5                   |                               | 22.5685         |
| 8                        | 12.5                          | 16.0844         |
| 8+12.5                   |                               | 19.5126         |

![Fig2 6mmP4+10.5mm test curve](image)

In the test, it can be found that no matter how large the diameter of the auxiliary rope is, the 6 wraps Prusik knot can hold the 10.5mm and 12.5mm main ropes well. As shown in Figure 3, on the 10.5mm main rope, the 6 wraps Prusik knot made of the 6mm rope is tightened and can hold the main rope better.
As the pulling force increases, the Prusik knot continues to hold the main rope with force, and the slope of its curve gradually increases. When the pulling force reaches 10.152KN, the Prusik knot has a small fall, and then continues to hold the main rope until the pulling force reaches 11.5242KN, the loop broke. The whole process, the prusik knot only slipped 24mm, and the curve was smooth, similar to a parabola. With the increase of the diameter of the auxiliary rope, the maximum pulling force that the Prusik knot bears also increases, especially the 8mm auxiliary rope reached 17.7263KN and 23.5087KN on the 10.5mm and 12.5mm main ropes, and the main rope skin was broken directly.

It can be seen that the force effect of the 6 wraps of Prusik knot is significantly better than the 4 wraps Prusik knot. On the 10.5mm main rope, all 4 wraps of Prusik knots failed. In the fire rescue, when it is necessary to grasp the main rope for fixed protection, for the sake of safety, 6 wraps of Prusik knot should be preferred. When flexible operation and more movements are required during the ascent or descent, 4 wraps of Prusik knot can be selected within the force range. The sliding effect is better. In order to ensure safety and improve the effect of grasping the main rope, two 4 wraps of Prusik knot can usually be used in series, which not only plays a safety protection role, but also has a good sliding effect.

2.2.2 Klemheist force test analysis
In the test, the Klemheist knot has more small falling phenomenons when it is tightened by force. During the sliding process, due to the unidirectional braking of the Klemheist knot, the tension on each wrap varies, and the pulling force of the front part is greater than the rear end part. The Klemheist knot is gradually tightened by force, the main rope bends and deforms with the force of the grab, and it rotates and winds around the knot. The bending angle of the main rope can reach 90°. At the same time, as the main rope deforms and rotates, the Klemheist knots will untie the unstressed rope loop. The main rope and the stressed rope loop are entangled to further grasp the main rope, which is also prone to emergency fall.

On the 10.5mm main rope, the 6 wraps Klemheist knot made of the auxiliary ropes of different diameters, as the diameter of the auxiliary rope increases, the maximum tension it receives increases accordingly. The 6 wraps Prusik knot made of 6mm and 7mm auxiliary ropes shows that the larger the diameter difference is, the smaller the slip distance is, and the stronger the main rope is, which is the same as the Prusik knot’s performance. As shown in Figure 4, the 6 wraps Klemheist knot made of 6mm auxiliary rope is on the 10.5mm main rope, the initial slip distance is larger, and the slope of the curve is smaller. As the tension increases, the knot gradually tightened, the main rope gradually bends and deforms, and its curve slope gradually becomes larger. When the main rope and the auxiliary rope are intertwined and bonded together, the main rope can be grasped firmly. The Klemheist knot also gradually evolved from a small drop to a larger drop, and finally stopped when the rope loop broke or
the main rope broke. Compared with the 6 wraps Prusik knot made of 6mm auxiliary rope, the number of the drops has increased significantly. It can also be seen that the inflection point at which the drop occurs has an upward trend. This shows that in the process of falling, the grasping force of the Klemheist knot is still increasing, so as to grasp the main rope more firmly.

On the 12.5mm main rope, the 6 wraps Klemheist knot made of three kinds of diameters all play a better role. According to the test data of the two main ropes, on the main rope of the same diameter, with the increase of the diameter of auxiliary rope, the maximum pulling force also increases, and the sliding distance also increases. The 8mm auxiliary rope even slips by 390mm. On the main ropes of different diameters, the same auxiliary rope made of the same wraps Klemheist knot, as the diameter difference between the main rope and the auxiliary rope increases, the sliding distance decreases, and the grip is firmer.

When the number of knot wraps is increased to 8, the force effect is significantly improved. On the 12.5mm main rope, the number of drops decreases in the test of the 8 wraps Klemheist knot made of 7mm auxiliary rope, and the slope of the curve increases. On the main rope of the same diameter, the Klemheist knot with different wraps made of the same diameter auxiliary rope will significantly reduce the slip distance as the number of wraps increases. On the main rope of 10.5mm, 6 wraps made of the auxiliary rope of 6mm, the slip distance is 195mm, while change to 8 wraps, the slip distance is only 35mm. Whether it is the main rope of 10.5mm or 12.5mm, the Klemheist knot can have a good performance. The maximum pulling force it receives increases with the diameter of the auxiliary rope, and the sliding distance also increases. As the diameter of the main rope increases, the maximum pulling force of the 8 wraps Klemheist knot made of 6mm and 7mm auxiliary ropes increases, and the sliding distance decreases, showing a better grip effect.

In summary, it can be seen that the Klemheist knot is mainly affected by the diameter of the main and auxiliary ropes and the diameter difference between the two ropes. The larger the rope diameter is, the greater the tensile force it can bear; the larger the diameter difference is, the greater the slip distance is. Compared with the 10.5mm and 12.5mm main ropes, the Klemheist knot not only increases the maximum pulling force, but also has a smaller sliding distance and a better force effect. Therefore, in fire rescue operations, if conditions permit, 12.5mm main rope should be preferred.

2.2.3 French knot force test analysis
Compared with the other two knots, the French knot has a different stress performance. The front wrap of the French knot is usually tightened by force, and the back wrap plays an auxiliary role. The foremost rope wrap is often the most stressed, which not only bites the main rope, but also presses down other stressed rope wraps. As the pulling force increases, the phenomenon of being unable to be suppressed
will often occur, resulting in a slow slip and a short drop. Because the force is parallel and in the same direction, and there is slow slip and short drop, the force can be distributed to the main rope, and the double rope loop of the French knot can bear the force at both ends, so the French knot can withstand greater tension and is not easy to break. During the French knot test, the main rope not only bears a great pulling force, but also bears the very large friction and squeezing force given to it by the auxiliary rope. After a force test of French knot, on the main rope, the place where the French knot passes becomes harder and has a higher temperature due to the greater force, and the rope skin is dyed with the colour of the auxiliary rope skin.

The 6 wraps French knot made of the three kinds of auxiliary ropes cannot hold the two kinds of main ropes, they are all failed. Increase the number of wraps to 8, on the 10.5mm main rope, the 6mm auxiliary rope can hold the main rope firmly. The other two kinds of the auxiliary ropes, due to the small diameter difference with the main rope, the French knot cannot hold the main rope and cause continuous slip and fail. The 8 wraps French knot made of the 8mm auxiliary rope cannot grasp the main rope even with the aid of both hands. After replacing the 12.5mm main rope, the three kinds of auxiliary ropes can hold the main rope firmly due to the increase of the diameter difference, and the maximum pulling force on the rope increases with the increase of the auxiliary rope diameter.

As shown in Figure 5, on the 12.5mm main rope, the 8 wraps French knot made of the 7mm auxiliary rope is similar to the Klemheist knot after being stressed in the initial state. Its sliding distance is larger and the slope of the force curve is relatively small. This is related to the similarity of the knotting methods of Klemheist knot and French knot. The difference is that the French knot has two loops which connect with the carabiner, so with the continuous increase of the tension, the French knot produces a small drop and evolves into a large drop, and the number of drops is significantly increased. It can also be seen from the Figure that the French knot disperses the pulling force due to the continuous falling and slipping, so the pulling force it bears is relatively large and it is not easy to break. After a drop, the curve starts to rise again and reaches a higher level.

The force effect of the 10 wraps French knot is similar to the 8 wraps French knot, but the 7mm and 8mm auxiliary ropes still fail to work on the 10.5mm main rope. For example, the 10 wraps French knot made of 8mm on the 10.5mm main rope, due to its characteristic of easy looseness, the French knot starts to slip continuously when the tension reaches 3.9130KN. The slip curve is gentle, which indicates that the French knot is subjected to parallel forces in the same direction. Once the slip occurs, the friction between the main rope and the auxiliary rope is less effective. Due to its own load limitation, the 6mm auxiliary rope cannot withstand the tension of 24.1279KN, and the rope loop breaks. Comparing the 8 wraps and 10 wraps French knots, it can be found that there is not much difference in the amount of tension. It can be seen that after the force of the French knot is exerted, whether increase the number of
wraps or not, the force effect changes not so much. This is because the force is in the same direction and parallel. The front wraps which hold the force are almost the same, and the back wraps play a support role and don’t hold too much tension.

3. Conclusion

(1) Comparison of force curve. Comparing the curves of three typical grab knots comprehensively, the force curve of the Prusik knot produces less drop than the other two grab knots. The force curve of the Prusik knot is relatively smooth, the slope is significantly larger than the other two grab knots, and the sliding distance is small, which shows that when it is holding the main rope firmly. It is precisely because of this characteristic that when firefighters use ropes to carry out rescue operations, it is relatively common to use a single Prusik knot or a series of double Prusik knots. The force curve of the Klemheist knot gradually evolves from a small drop to a large drop. The inflection point of the drop has an upward trend. Its slope is smaller than Prusik knot, and the slip distance is larger than Prusik knot. The force curve of the French knot has significantly more drops than the other two grab knot. The possibility of the fall and the slippage is often larger but it is not easy to break. Due to its special knotting method and force direction, the main force is the friction between the main and auxiliary ropes, and the slip curve is relatively smooth.

(2) Comparison of the force effect of test. The force effect of the three kinds of grab knots is related to the respective diameters of the main and auxiliary ropes and the diameter difference between the two ropes. The maximum tensile force experienced increases with the increase of the rope diameter. The larger the diameter difference between the main and auxiliary ropes is, the smaller the slip distance of the grab knots are and the stronger the grab knots are. Tests show that the Prusik knot has a relatively smaller slip distance than the other two grab knots, and the grip is firmer. The main feature of the Klemheist knot is that it is easy to cause the main rope to bend and deform. The main rope and the auxiliary rope are entangled and bonded together, and it is easy to fall as the tension increases. The French knot double rope loops are stressed, and the tensile forces are parallel to the same direction. After the French knot is tightened, slow slippage and falling will occur continuously. Due to this kind of slow sliding and falling, the sliding distance is relatively large, and the tensile force is distributed on the main rope, which can withstand a large force without breaking, and its effect is relatively good when using in the falling protection.

(3) Analysis of static safety factor. Each piece of equipment of rope rescue has its own static safety factor, and the entire rope system has the lowest static safety factor. Most rescue teams use a static safety factor between 5:1 and 15:1. In actual operations, the minimum breaking strength and maximum breaking capacity should be estimated according to the actual situation. Take 3 persons as an example, set 100KG per person, the total weight will be 300KG. In reality, the test of the rope rescue system shows that the system built by it is close to 2.5 times of the static load (this is due to the nonlinear behaviour of the rescue rope elongation and the effect of the tightening of the knot). Then the tension of the rope can reach 7.5KN instantaneously. At this time, if firefighters choose a system above 5:1, they should choose a combination system that can withstand at least 15KN, and its instantaneous tension is less than the maximum load capacity of the combined system. According to the test data, if the Prusik knot is used on the 10.5mm and 12.5mm main ropes, the 6 wraps Prusik knot made of 6mm auxiliary rope can withstand the maximum pulling force of 11.5542KN and 13.8088KN respectively. For safety reasons, the 6mm auxiliary rope cannot be used for rescue operations, and the 12.5mm main rope is preferred if conditions permit. The selection of other grab knot is the same. If there are other factors, the coefficient should be corrected to obtain the reference tensile value, and the selection of rope equipment and the selection of grab knot combinations should be reconsidered to ensure the safety of rescue operations.

(4) Selection and combination of ropes in the actual operation. Besides the static safety factor, another thing to note for firefighter is the selection and combination of the diameter of the main rope and the auxiliary rope. The diameter of the auxiliary rope for making the grab knots should be approximately 60% to 80% (about 2/3) of the diameter of the main rope[4,5]. If the auxiliary rope is too
thin, it will be easy to tighten and grasp the main rope, but it is difficult to move freely and the load-bearing weight is relatively small. If the auxiliary rope is too thick, there is not enough friction to grasp the main rope. Taking the above example as an example, still choose to make 6 wraps of Prusik knot. If the main rope is 10.5mm, the diameter of the auxiliary rope is only 60% of the diameter of the main rope. However, according to the maximum pulling force it needs to bear and the combination of the ropes, that is, the 7mm auxiliary rope is more suitable; if the diameter of the main rope is 12.5mm, the 8mm auxiliary rope is more suitable. This rule applies to the selection of other rope rescue equipment.

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**References**

[1] VDiff Climbing. The Trad Climber's Guide To Problem Solving: Self-Rescue Techniques(2019).
[2] Yu-Hai Zhang, Fu-Chun Shen. The bowline's safety analysis in rope rescue. J. Fire Science and Technology, (2019).
[3] James A. Frank, Jerrold B. Smith. CMC Rope Rescue Manual(2014).
[4] Vines Tom. Hudson Steve. High Angle Rescue Techniques(2012).
[5] Loui McCurley. Professional Rope Access: A Guide To Working Safely at Height(2016).