Investigation of a Passive Capstan Based Grasp Enhancement Feature in a Voluntary-Closing Prosthetic Terminal Device

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Abstract— **Body-powered prosthetic terminal devices fall into two main categories: voluntary-closing devices, which require the user to exert a force to maintain a grasp, and voluntary opening devices, which generally utilize springs to close and maintain a force. As a result, voluntary-closing devices often have a locking feature that allows the user to relax and transport objects while maintaining a firm grip. In this paper, we examine a new type of capstan-based passive brake mechanism in a voluntary-closing prosthetic terminal device. Three different mechanisms were compared on the benchtop and with human subjects: the passive capstan grasp enhancement, a "pull-to-lock, pull-to-release" mechanism, and a manual cable locking mechanism. Standard tests of prosthetic device dexterity, including the Box and Blocks test and Southampton Hand Assessment Protocol, were performed with an instrumented prosthesis socket simulator with each device. While results are similar across the three mechanisms, the passive capstan mechanism does not require a physical user input to engage or disengage the lock, adding a benefit over the existing mechanisms.**

I. INTRODUCTION

During their everyday lives, most upper-limb amputees choose body-powered over electrically powered terminal devices due to their durability, reliability, proprioceptive feedback, and low cost [1]. The devices can be "voluntary-opening", where the actuation force opens the hand and a passive spring defines the return and grip force, or "voluntary-closing", in which the user applies force to close the device and grasp objects, with springs opening the device [2,3]. A limit to voluntary-closing systems is that the user has to sustain the grasping force over the length of the grasp, which can be especially difficult to coordinate when actively moving the prosthesis. As a result, voluntary-closing devices generally incorporate a locking mechanism in order to allow the user to relax the tendon after grasping [4].

In this paper, we investigate a passive capstan-based braking mechanism for voluntary-closing terminal devices (TDs). Existing locking solutions, described in depth in Section II, generally require the user to manually engage and disengage the lock by "flipping" a mechanical switch or exerting a force to lock, and then exerting another force to disengage the lock. Alternatively, the passive capstan mechanism utilizes a one-way clutch and friction to provide a holding force that maintains a grasp after the user exerts the initial force. Once the user relaxes this input force almost completely, the object is released.

In the following sections, we introduce the design and integration of the capstan mechanism in a voluntary-closing U.S. Army Prosthetic Research Laboratory (APRL) hand, benchtop testing of the different locking mechanisms, human subject Box and Blocks and Southampton Hand Assessment Protocol (SHAP) testing, and analysis of the different mechanisms.

II. COMMERCIAL LOCKING MECHANISMS FOR VOLUNTARY-CLOSING PROSTHESES

The goal of any locking mechanism for upper limb cable driven prostheses is to maintain a grip force on an object while removing both the physical and mental burden of continually pulling on the body-powered harness cable. Here, we will review the two common methods used in voluntary-closing, cable driven, body-powered prostheses.

A. Manual Cable Lock (TRS, Inc. Sure-Lok Cable System)

The manual locking mechanism [5], shown in Fig. 1a, is mounted in-line on the input cable coming from the harness. This mechanism uses a mechanical rocker switch that engages or disengages the lock. When the rocker switch is engaged to lock, a cam surface rotates and compresses the input cable against a hard stop, which locks the cable in place. When the switch is disengaged, the cam surface releases the force on the input cable allowing it to move freely through the mechanism.

B. Pull-to-lock, Pull-to-release

The pull-to-lock, pull-to-release mechanism is integrated into the actuation of the APRL prosthetic devices [6], shown in Fig. 1b. Locking the position of the actuation cable is achieved using a bistable cam mechanism. Each pull from the input cable changes the state of the cam to either locked or unlocked. When the input force relaxes, the cam locks the mechanism in its current position. When the user inputs another pulling force, the cam switches states, and returns to

a) b)

Fig. 1. a) The manual locking feature is implemented on the outside of the prosthetic socket and is operated with an able-hand. Here, we show the TRS, Inc. Sure-Lok Cable System [5], b) The pull-to-lock-pull-to-release locking feature is shown inside of the APRL voluntary-closing hand [6].

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the open position with the hand. This type of feature has been implemented by Hosmer® in the APRL hand as well as by Ottobock® in many of their voluntary-closing hands, like their Cable System Hand [7].

III. Capstan Based Grasp Enhancement Mechanism

The desired function of the grasp enhancement mechanism is to maintain the tension of the tendon (maintaining grasp force) while the user of a voluntary-closing prosthetic device relaxes the input force. A similar device has been implemented in robotic systems to improve the holding capabilities of tendon driven actuators [8].

Grasp enhancement is achieved through the use of a one-way clutch mounted on a non-rotating shaft. A capstan sleeve is mounted over the one-way clutch, which has the input cable wrapped around it. The cross-section of the design can be seen in Fig. 2. The input cable is anchored on a user's harness, which then feeds into the mechanism, wraps around the capstan sleeve, and is output into the actuation of the prosthetic device. It should be noted that the grasp enhancement mechanism can be disabled if desired, by allowing the shaft to rotate, which allows free rotation in either direction.

When the user exerts an input force, F_{act}, the input cable is pulled, and the one-way clutch freely rotates in the pulling direction causing the prosthetic device to close. After the user grasps an object, the input force can be relaxed. The mechanism resists the spring force, F_{out}, of the prosthetic device, which is trying to open, to maintain the grasp force. The friction between the capstan sleeve and the cable wrapped around it, F_{fric}, produces the necessary holding force. Once the input force is completely relaxed, the holding friction force will be overcome, and the prosthetic device will open even though the capstan sleeve and one-way clutch do not rotate. The small amount of cable force required to rotate the capstan pulley in the free-spinning direction is small and therefore can be neglected compared to the large friction force between the cable and the pulley when the cable is being released. There is a small torque M_c, required to overcome the friction on the one-way clutch and capstan sleeve [8]. Fig. 3b illustrates that the friction forces between the cable and the capstan pulley are direction dependent and therefore help to maintain a grasp yet do not add additional cable forces when closing the hand.

A. Force Analysis

The force analysis relies on the classic capstan equation [9],

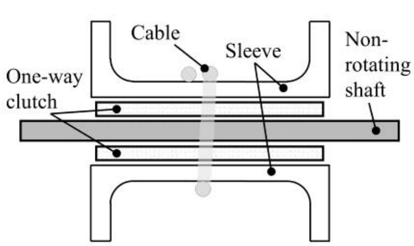

Fig. 2. Cross-section of the capstan grasp enhancement mechanism

$$F_{out} = F_{act} e^{\mu\theta} \tag{1}$$

where, F_{act}, F_{out}, μ, and θ are the input force, output force, static friction coefficient, and wrap angle, respectively. $F_{act}e^{\mu\theta}$ is the holding force. The wrap angle is the angle of contact of the tendon around the capstan, i.e., $\theta = 360^{\circ}$ when the cable is wrapped around the capstan once. We will illustrate the behavior of the capstan based system using Fig. 3. In Fig. 3b, the user exerts an input force to close the prosthetic device and the one-way clutch with capstan sleeve rotate freely. Therefore the force of closing the hand is

$$F_{act} = F_{out} + F_{fric\_bearing} \tag{2}$$

where $F_{fric\_bearing}$ is the small resistance of the free rotation of the one-way bearing. Once the user achieves a grasp, and lowers the input force, as shown in Fig. 3c, the one-way bearing locks in position and the friction of the tendon against the sleeve, $F_{fric\_capstan}$, helps to maintain the grasp force. The force can then be described as

$$F_{out} = F_{act} + F_{fric\_capstan}, \tag{3}$$

In order to maintain grasp, the condition of the classical capstan equation is

$$F_{out} \leq F_{act} e^{\mu\theta}. \tag{4}$$

If F_{out} is less than the holding force, than the cable will not be unwound, and the grasp will be maintained.

In Fig. 3d, the user relaxes the input force to then open the prosthetic device. Because of the behavior of the capstan mechanism, the grasp force is maintained until the holding force drops below the force required to prevent slipping of

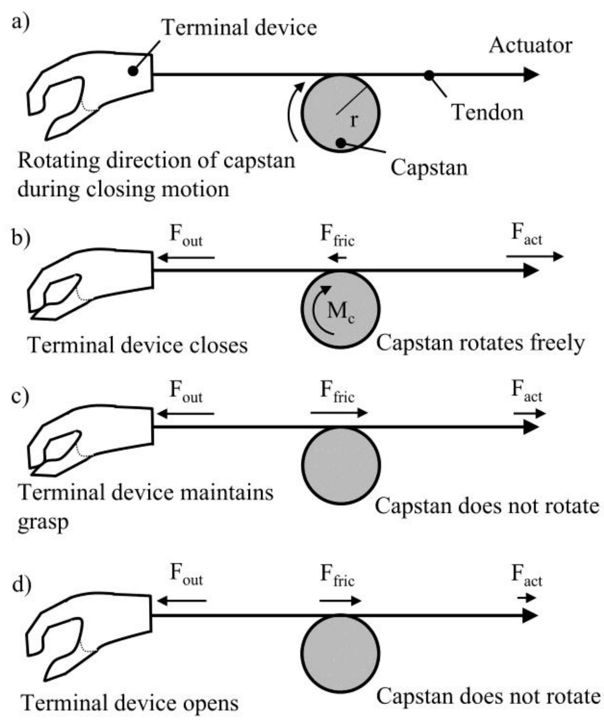

Fig. 3. a) Schematic diagram of the mechanism. b) Mechanism while terminal device is being closed - force to terminal device is the same as cable input force. c) Mechanism locked and maintaining grasp force - friction force on capstan builds while trying to rotate in the opening direction. d) Mechanism releasing and terminal device is opened by reducing actuation force.

the cable on the capstan surface. Slip of the tendon over the capstan will occur, which then opens the prosthetic device releasing the grasp, when the following condition is met

$$F_{out} > F_{act} e^{\mu\theta} \quad (5)$$

B. Work Analysis

As a metric of the effort put in by the user to operate a terminal device, the amount of mechanical work exerted during grasping and transporting an object was calculated. The total amount of work, W_{Tot}, can be computed by summing the amount of work required to close and grip an object, W_{Grip}, the work required to hold the object, W_{Hold}, and the work to release the object, $W_{Release}$. Using the capstan feature, the holding force will be reduced by the capstan effect. The pull-to-lock mechanism and manual cable lock mechanism lock the cable completely and therefore do not require any harness forces to hold an object. Lastly, not using a locking feature will yield a holding work that is dependent on the amount of time a user needs to hold an object. The work for each locking feature is calculated using

$$W_{Tot\_NoLock} = W_{Grip} + W_{Hold}(t) + W_{Release} \quad (6)$$

$$W_{Tot\_Capstan} = W_{Grip} + W_{Hold}(t)/e^{\mu\theta} + W_{Release} \quad (7)$$

$$W_{Tot\_PullLock} = W_{Grip} + W_{Release} \quad (8)$$

C. Capstan Sleeve Geometry

As seen in Fig. 2, the capstan sleeve has a unique geometry. This geometry was designed to prevent any failure in the grasp enhancement mechanism due to cable tangling or overlapping on itself. If the cable overlapped on itself and became tangled, this would cause a permanent lock which is not desirable in this application. Also, as the cable translates around the sleeve, it moves laterally parallel with the axis of the non-rotating shaft. This lateral movement could cause the cable to fall off the capstan, which would then also cause the capstan to fail.

First, the outer diameter of the capstan sleeve, d_{sleeve}, (surface that is in contact with the cable) is determined knowing the length of excursion, $L_{excursion}$, of the input cable. An average cable travel length of 45 mm [4] was used in calculation of this grasping mechanism. To then solve the outer diameter of the sleeve, the circumference of the sleeve was designed to match the excursion length, so only one rotation of the capstan pulley is required for full excursion of the hand. Next, the "lips" were made at the edges of the sleeve to prevent the cable from falling off the capstan. The diameter of the lips should be at least three times the diameter of the cable plus the diameter of the sleeve. This ensures even with some cable overlap, it will still not fall off of the capstan.

The next important design feature was the use of a fillet between the outer diameter of the sleeve and the lip. As the capstan sleeve rotates in the pull force direction (closing the prosthetic device), the input cable wrapped around the sleeve travels laterally towards the lips. When the one-way clutch is engaged, the input cable has to travel laterally in the opposite direction on the sleeve to make-up for the lateral translation. In order to prevent input cable overlap the diameter of the sleeve only allowing one rotation and the fillet are utilized as key features in the design. The fillet allows the cable to continue to travel laterally without the cable compressing against itself on the lip. This is exaggerated for demonstration in Fig. 4. This radius, r_{fillet}, that best achieves these goals has been experimentally determined to be

$$r_{fillet} \geq 1.5\, d_{cable} \quad (10)$$

A fillet radius that doesn't meet this condition was found to tangle from cable overlap during initial design testing.

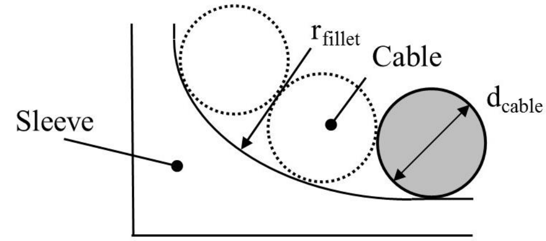

Fig. 4. A fillet between the outer diameter of the sleeve and the lip prevents cable overlap as the tendon moves laterally.

D. Capstan Testing

1) Test Setup

The test setup for preliminary testing incorporated two loadcells to measure the input and output forces. The output force loadcell was fixed to a wall with a spring (spring constant = 0.91 N/mm) to represent a voluntary-closing prosthetic device. The input force loadcell was attached to the end of a linear actuator. The grasp enhancement mechanism was then fixed in-line between the two loadcells. The standard prosthetic 400 ULTRA Spectra cable [5] with 0.46mm diameter was used as the tendon line. The tendon line was the wrapped around the grasping mechanism and secured onto the spring and input loadcell. The actuator then retracted to simulate an input force closing the hand, and then was released. The input and output forces were recorded as well as the position of the actuator to determine the efficiency of the grasping mechanism and the excursion of the tendon.

2) Material and Wrap Testing

In order to determine the optimal design for the capstan grasp feature, various materials – polished and sand-blasted aluminum, steel, and acrylic – were tested with one, two, and three wraps around the capstan. Each material went through three cycles of the capstan being engaged and disengaged (actuator pulling and returning to original position). In one cycle, the actuator pulls the tendon as the capstan rotates freely. The actuator then returns to its original position, relaxing the force, while the capstan feature maintains the output force (holding force). Finally, the tendon is relaxed and slides around the capstan back to original position. Results showed an output force (holding force) of 35 N could be maintained with 15-20 N of input force for one wrap, 7-12 N with two wraps, and 1-5 N with three wraps. The friction coefficient was also calculated to evaluate the material and wrap angle effects on the capstan. The friction coefficient can be solved for using the input and output force data collected from testing by solving Eq. 1 for the friction coefficient

$$\mu = \ln (F_{act} / F_{out}) / \theta \quad (11)$$

where θ is in radians. The friction coefficient for sand-blasted aluminum against Spectra ranges between 0.15-0.175, while the friction coefficient for all other materials tested against Spectra is between 0.06-0.1.

3) *Final Capstan Design*

Sand-blasted aluminum with a wrap angle between 360-720° was chosen as the final design due to the larger friction coefficient which yields an optimal capstan ratio. Larger than two wraps will not be used in this application since it is difficult for the user to remove all the tension required to release the object (0-5N).

IV. Benchtop Analysis of Locking Features

In order to have a controlled test of the three mechanisms a fixed bench setup was utilized. The three mechanism were each integrated into the APRL hand, and the cable pull was controlled using a linear potentiometer.

A. *Evaluation Test Setup*

Similar to the preliminary test setup, two loadcells were again used to measure input and output force, with the input force measurement loadcell being attached to the actuator. However, the output force now is the grip force between the two closing fingers and opposing thumb of the APRL hand. The APRL hand was then attached to the input cable (400 ULTRA Spectra cable used for the capstan, stainless aircraft cabled used for the other mechanisms) and fixed. The measured opening width of the APRL hand in its precision grasp is 45 mm, and the width of the loadcell placed in the hand is 34.5 mm. The setup is shown in Fig. 5. In order to determine the capstan grasping efficiency, it was compared against the pull-to-lock, pull-to-release mechanism in the APRL hand, as well as the TRS, Inc. manual cable lock. Each

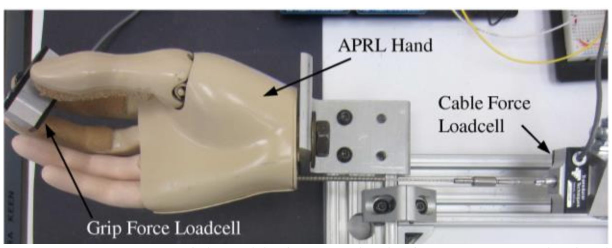

Fig. 5. Measurements of the cable force and grip force were acquired using a standard two-loadcell setup for the three different locking features.

of these mechanisms were put in-line with the input cable that fed into the hand. A pulling force of 100 N was used as an upper bound of pull force from the user.

B. *Mechanisms Analysis*

Fig. 6 shows the comparison of grip force to pull force, as is standard in the analysis of prosthetic terminal devices [4]. The three mechanisms go through one cycle of the APRL hand starting open with no pull force, closing and gripping on a loadcell, the grasping/locking mechanism engaging and the pull force relaxing, and finally disengaging the grasp/lock and re-opening the hand. The cable force required to close the APRL hand to the point of contacting the loadcell is 30 ± 3 N.

The three mechanisms all show a drop in grip force after the grasping/locking mechanism is engaged and the pulling force is relaxed. The drop in grip force is 10 ± 1.5 N for the capstan (both one and two wraps) and the pull-to-lock, pull-to-release mechanism. A drop in grip force of 17 ± 1 N is seen in the TRS, Inc. manual cable lock. Unlike the pull-to-lock, pull-to-release mechanism and the TRS, Inc. manual cable lock, the capstan grasp enhancement feature does not require an additional pull force to disengage the grasping mechanism. However, the capstan feature with two wraps does still require 10-15 N of pull force on the input cable to maintain a grip force of 40 N. The pull-to-lock, pull-to-release mechanism and TRS, Inc. cable lock both allow the pull force to go to 0 N while maintaining a grip force between 30-40 N.

V. Instrumented Harness Testing of Locking Features

Since the ultimate goal of the capstan grasp enhancement feature is to be used to help those who use body-powered prostheses, we utilized a prosthetic simulator to mimic typical prosthesis behavior and actuation. The APRL hand was put on a prosthetic simulator and operated by able-body test subjects. The study was reviewed and approved by the Yale Human Subjects Committee, Protocol Number 1411014968 [10], and testing was done in accordance to the approved IRB.

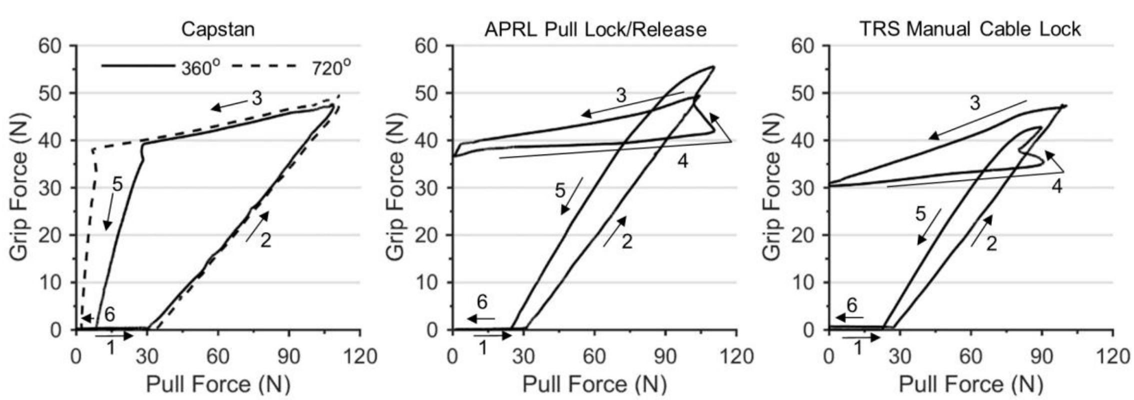

Fig. 6. Pull force vs. grip force comparison of three locking mechanisms on the APRL hand. Explanation of steps: 1 – Input cable pulls to activation force, the fingers close. 2 – Fingers grasp the loadcell, and the grip force increases. 3 – Input cable relaxes, the lock is activated and there is a slight grip force drop. 4 (Step not applicable to capstan lock) – Input cable pulls again, lock is disengaged. 5 – Cable relaxes again (disengages capstan lock), grip force decreases. 6 – Fingers open

A. Test Setup

The test subjects used a standard figure-of-nine harness [11,12] to operate the APRL hand on the prosthesis simulator. A loadcell and cable excursion sensor were mounted in-line with the input cable. Each locking feature was then mounted in-line in order evaluate each method. The capstan mechanism used two complete wraps of the tendon in testing. Finally, a data acquisition system was used to collect all force, excursion, and time data. An image of the able-body testing setup can be seen in Fig. 7.

B. Box and Blocks Test

One subject performed a standard box and blocks test [13] with their dominant right hand five times each with the capstan grasping mechanism, the pull-to-lock, pull-to-release mechanism, and then without a locking mechanism. The TRS, Inc. cable lock was not used for the test because the user does not need to grasp each block for an extended period of time. Fig. 8 shows the subject's force and excursion as a function of time in completing five successful grasps and releases of a block. The graph for the capstan mechanism demonstrates that the input force drops after the block has been grasped, while the cable excursion maintains its position. The force and excursion graph for the pull-to-lock, pull-to-release mechanism shows that after the user grasped the block, they could completely relax the input force while the excursion was unchanged, but then had to re-exert a higher force than the initial input force to release the block. Finally, when the user did not have a locking feature, the force and excursion graph show that the subject had to maintain the grip force and peak excursion length while transferring the block before releasing.

Lastly, the total amount of work done using each mechanism was calculated using the input force and input cable excursion data, as shown in Table I. The capstan uses the least amount of work compared to the pull-to-lock and no-lock trials, with no-locking requiring the most user energy.

The average amount of blocks transferred in one minute for non-impaired right handed male between the ages of 20-34 is between 85.2-88.0 [13]. The reduced function of the APRL terminal devices is shown in Table I with the number of blocks being transferred during the tests ranging between 15 and 20.

TABLE I. FIVE TRIAL AVERAGE NUMBER OF BLOCKS AND TOTAL WORK (J) USED DURING THE BOX AND BLOCKS TEST

Box and Block Test			
	Capstan	*Pull*	*No-Lock*
Number of Blocks	17	15.8	18.8
Total Work (J)	967.5	1053.5	1351.5

C. SHAP Testing and Analysis

Three human subjects performed the SHAP test with their dominant right hand with the capstan grasping mechanism, the pull-to-lock, pull-to-release mechanism, and then without a locking mechanism. The SHAP test is a standard test of upper extremity dexterity and is frequently used to evaluate upper limb prosthetic devices [14]. Each user completed the SHAP test three times using each of the different locking features in random order.

Fig. 7. An instrumented body powered harness was used to evaluate the various locking features on a prosthesis socket simulator. The simulator allows able-body subjects to operate various prosthetic terminal devices in a similar way to how an amputee would operate the device.

Using the times to complete each task, the SHAP index of function (IOF) scores were calculated and are shown in Fig. 9. The scores of the SHAP test are normalized by the time required for able-body subjects using their natural hand to complete the same tasks. Completing all the tasks in the same time as the typical unimpaired user would result in a score of 100. Previous work on testing with able subjects on the SHAP test showed average scores between 96.7 and 99 [15,16]. The low scores during testing with the APRL hand are a result of the reduced function when using a prosthesis (higher scores indicate better performance).

The amount of work done to complete each task was calculated using the input cable force and input cable excursion and averaged for the three users to find a total amount of energy used to complete the SHAP test as shown in Table II. The work done for the light and heavy abstract objects was summed as well as the Acts of Daily Living (ADL) tasks to determine any differences in work for these different tasks.

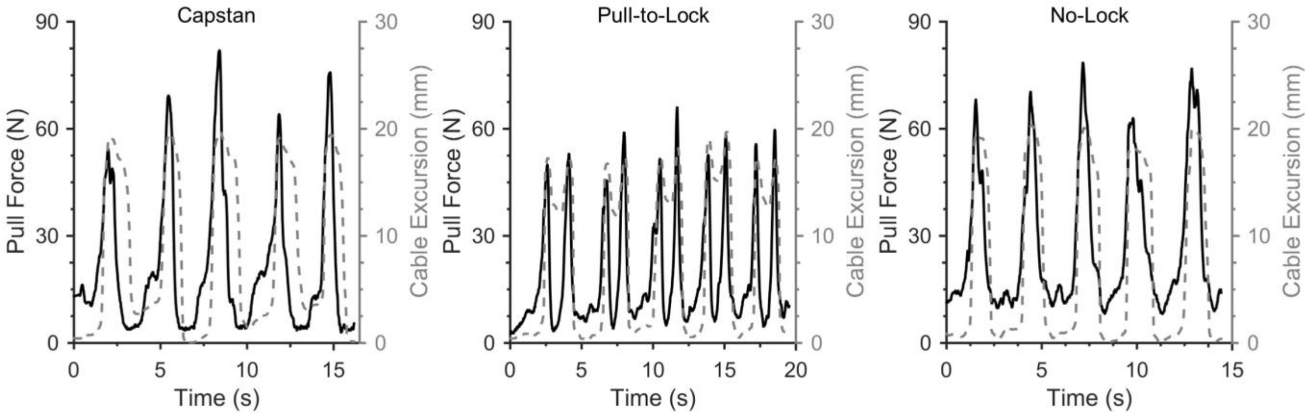

Fig. 8. Pull force and Input Cable Excursion vs. time for Box and Blocks test showing five successful grasps for the capstan, the pull-to-lock, and no-lock

TABLE II. AVERAGE WORK USED DURING SHAP TEST

SHAP Test - Work (J)				
	Task	*Capstan*	*Pull*	*No-Lock*
Light	*Sphere*	9.4	11.1	11.0
	Tripod	165.4	333.8	139.4
	Power	103.3	207.0	117.9
	Lateral	142.0	170.9	274.9
	Tip	307.8	258.9	288.2
	Extension	444.6	272.8	379.6
Heavy	*Sphere*	42.0	498.0	42.1
	Tripod	108.7	726.6	134.8
	Power	208.8	233.8	180.0
	Lateral	168.7	402.0	283.5
	Tip	222.2	231.4	255.9
	Extension	316.2	307.3	285.1
ADL	*Coins*	1735.2	1818.1	1454.0
	Button Board	3148.8	2963.3	2448.7
	Food Cutting	2251.5	1763.9	4823.1
	Page Turning	323.4	377.2	283.0
	Jar Lid	780.0	598.3	464.4
	Jug Pour	2455.6	1142.5	2909.5
	Carton Pour	1846.2	594.4	2148.1
	Full Jar	94.8	163.0	176.2
	Empty Tin	79.1	418.0	489.1
	Tray	265.5	334.2	255.1
	Key	196.7	214.9	245.4
	Zip Open/Close	1050.6	557.0	846.5
	Screw	425.6	1307.8	641.6
	Door Handle	180.6	155.9	202.5
Abstract Total Work (kJ)		*2.2*	*3.7*	*2.4*
ADL Total Work (kJ)		*14.8*	*12.4*	*17.4*
SHAP Test Total Work (kJ)		***17.1***	***16.1***	***19.8***

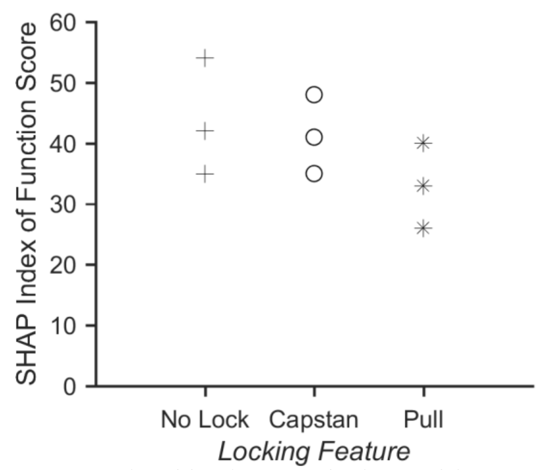

Fig. 9. SHAP Index of function scores for the use of the capstan feature, pull-to-lock pull-to-release mechanism, and no lock. Here, higher scores indicate better performance

VI. DISCUSSION

A. Capstan Grasp Enhancement Feature

The capstan grasp enhancement feature shows similar results to the other locking mechanisms. It allows users to passively engage or disengage the feature during normal tasks while maintaining a grasp without having to continually exert a high input force. When using the capstan based grasp feature, the users explained that it was easier to keep grasping the object, however, the release was delayed from when the users attempted to release the object. This made it difficult to place down objects accurately without completely stopping the hand from moving. This delay could be a result of the slip driven return of the capstan mechanism which causes the tendon to slowly release once below the threshold. The users also described a lack of feedback regarding when the capstan was locked or not. Users stated that this feature still required mental effort, but got easier with practice.

B. APRL pull-to-lock, pull-to-release

The APRL pull-to-lock and release feature shows the least amount of lost grip force when the lock is engaged and pull force is relaxed. However, it does require the user to re-exert the initial pull force or more in order to disengage the lock. If the user is grasping a soft or more fragile object, this can become a problem, as grip force feedback is limited in terminal devices.

The users described that using this device was counterintuitive to how hard it was necessary to grab an object while locking the hand. If an object was grabbed too hard, then the release would require a greater force to overcome the internal spring, leading on two occasions to a broken actuation tendon. However, as the users became aware of this locking and unlocking, the hand became more intuitive and they were able to complete the different tests.

C. *TRS, Inc. manual cable lock*

The TRS, Inc. lock requires the user to manually engage or disengage the locking switch after completing the grasp. This locking feature is beneficial to grasps that need to be held for an extended period of time. It's also beneficial mentally to have the direct feedback that the grasp is locked. However, it can be difficult for a user to maintain the grip force while having to engage the lock with their other hand. It also might not always be possible to engage the lock, as is the case in bi-manual tasks. When disengaging the lock, the user is required to re-exert a pulling force. This prevents users from losing a grasp if the lock becomes disabled, but also requires the user to exert more energy to release the object similar to the pull- to-lock mechanism.

D. *Box and Blocks and SHAP Testing*

The box and blocks test revealed that the capstan required less energy from the user compared to the pull-to-lock and no-lock, averaging 17 successfully transported blocks. The no-lock required significantly more energy from the user in order to maintain the grasp of the block while it was transported. However, the no-lock was the quickest at getting the most amount of blocks successfully transported. The pull-to-lock, pull-to-release was the slowest only averaging 15.8 successfully transported blocks. This is due to the extra time to unlock the mechanism.

The SHAP test demonstrated the importance of the amount of time grasping an object. The results show that no-locking feature scored the best overall with the capstan having a similar overall IOF score. The pull-to-lock mechanism scored the lowest due to the extra time to unlock the mechanism. Analyzing the amount of work done, it is seen the capstan feature requires the least amount of mechanical work for the light and heavy abstract object tasks. However, the pull-to-lock mechanism requires much less work in the ADL tasks and total work overall. The pull-to-lock mechanism allowed the subjects to grasp the objects in the ADL tasks and maintain that grasp throughout the test, which was very helpful in tasks like the food cutting, jug pour, and the carton pour. The no-lock performed well with the abstract objects because users had to quickly transport the different shapes over a short distance. However, not having a locking feature also fatigued many of the users throughout the ADL tasks due to the constantly required input force to maintain a grasp while completing the task.

It should be noted that the APRL does not have a lateral grasp, making it difficult to complete SHAP test tasks requiring a lateral grasp.

VII. Conclusion and Future Works

A method for reducing the amount of force required to continuously grasp an object in tendon-driven systems is necessary to help reduce user fatigue. For body-powered voluntary-close prosthesis, a capstan mechanism put in series with the actuated tendon allows the user have a lower required actuation force to continuously grasp an object. The release threshold of this device is tunable and allows for a range of release forces. The capstan mechanism tested similarly to that of a pull-to-lock, pull-to-release mechanism and no-locking mechanism in the box and blocks and SHAP test. Although the capstan mechanism does not allow full release of the tendon tension, it is the only mechanism of the three that requires no additional user interaction to operate. It also has an equilibrium tradeoff between speed and required energy. Not having a locking mechanism proved to score the best in the SHAP test due to quickness, but also caused the most fatigue with the amount of energy required. The pull-to-lock mechanism scored the lowest in the SHAP test, but required the least amount of energy. The capstan scored similarly to no-locking mechanism on the SHAP test, but required a lower amount of work than having no-locking mechanism.

In the future we would like to evaluate this capstan mechanism with more able-bodied subjects and amputees to better evaluate the functionality of the device in everyday situations. We would like to compare this mechanism to those in many other voluntary-close terminal devices to determine user preferences for various tasks.

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