Cable-Driven Finger Exercise Device With Extension Return Springs for Recreating Standard Therapy Exercises

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Finger therapy exercises, which include table top, proximal-interphalangeal blocking, straight fist, distal-interphalangeal blocking, hook-fist, and fist exercises, are important for maintaining hand mobility and preventing development of tendon adhesions in postoperative hand-injury patients. Continuous passive motion devices act as an adjunct to the therapist in performing therapy exercises on patients; however, current devices are unable to recreate these exercises well. The current study aimed to design and evaluate a finger exercise device that reproduces the therapy exercises by adopting a cable-actuated flexion and spring-return extension mechanism. The device comprises of phalanx interface attachments, connected by palmar-side cables to spooling actuators and linked by dorsal-side extension springs to provide passive return. Two designs were tested whereby the springs had similar (design 1) or different stiffnesses (design 2). The device was donned onto a model hand and actuated into the desired therapy postures. Our findings indicated that design 1 was able to recreate table top, straight fist, and fist exercises while design 2 was capable of further replicating distal-interphalangeal blocking, proximal-interphalangeal blocking, and hook-fist exercises. This work demonstrated the possibility of replicating finger therapy exercises using a cable-actuated flexion and spring-return extension design, which lays the groundwork for prospective finger exercise devices that can be donned on patients to assess the efficacy in postoperative joint rehabilitation. [DOI: 10.1115/1.4025449]

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1 Introduction

Finger therapy exercises are important for maintaining hand mobility and preventing development of tendon adhesions in postoperative hand-injury [1]. These exercises include the table top, proximal interphalangeal (PIP) blocking, straight fist, distal interphalangeal (DIP) blocking, hook fist, and fist exercises (Fig. 1). The execution of these exercises would usually necessitate the presence of an occupational therapist that will assist the patients in performing the exercises. However, the therapist will not be present all the time to assist the patient with the therapy exercises, which thus leads to relatively less therapy time and slower recovery time compared to a scenario whereby the patients' fingers can be exercised continuously.

Continuous passive motion (CPM) devices are considered to be a good adjunct to the therapist, especially in various joint rehabilitation procedures involving the wrist and knee [2–4]. Rozencwaig et al. [4] reported that the range-of-motion (ROM) of the affected wrist recovered faster in participants receiving both CPM and occupational therapy as compared to occupational therapy alone. Lenssen et al. [2] further demonstrated that prolonged knee CPM use has a short-term benefit on the ROM in patients after total knee arthroplasty. However, for the fingers which consist of multiple joints, namely, the distal interphalangeal, proximal interphalangeal, and metacarpophalangeal joints (MCP), the therapeutic motions are relatively more complex compared to that of the wrist or knee [1,5].

Although current hand CPM devices are capable of manipulating the hand into simple fist flexion [6–10], they are unable to recreate the effective therapy exercises that therapists performed on patients. For most of these devices, their attachments to the patient's fingers are usually at the tips, and CPM is introduced by moving the fingertips proximally into a clenched fist posture, followed by moving the fingertips distally into an open palm posture. The entire cycle is then repeated slowly for the number of prescribed hours per day.

The purpose of the current study was to design and evaluate a finger exercise device that can recreate the therapy exercises, which are typically performed by occupational therapists. In our design, we adopted a cable-actuated flexion and spring-return extension mechanism in order to minimize the number of actuators required for manipulating each finger joint. We also tested the spring-return extension mechanism with different spring stiffnesses between the finger joints to examine the possibility of recreating relatively more complex therapy exercises.

2 Methods

Cable-Actuated Flexion and Spring-Return Extension Design. The finger exercise device design primarily comprises of interface attachments, cables, spooling actuators, and springs. This device was donned on the index finger of a model hand that possesses all three finger joints (DIP: 5–85 deg flexion, PIP: 4–85 deg flexion, and MCP: 5–89 deg flexion) with sagittal plane range-of-motion fairly similar to that of a typical human finger (DIP: 0–80 deg flexion, PIP: 0–100 deg flexion, and MCP: 0–90 deg flexion) [3]. Each of the interface attachments is made up of two rigid plastic curved plates connected by elastic bands, and they are mounted onto the phalanges and metacarpus of the model hand (Fig. 2).

Cables (nylon-coated stainless steel wire rope 90#, McMaster, USA) were used to connect the palmar side of the phalanx interface attachments for the DIP, PIP, and MCP joints to the spooling D-, P-, and M-actuators (placed on the forearm of the model hand), respectively, in a manner similar to the tendon-pulley system in the human finger anatomy [11]. Therefore, each actuator

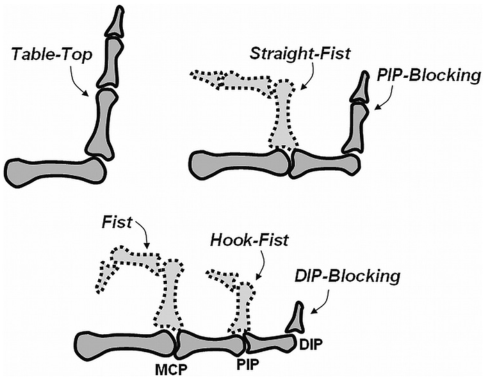

Fig. 1 Types of therapy exercises performed on the finger or hand during postoperative rehabilitation. The exercises include table top, PIP blocking, straight fist, DIP blocking, hook fist, and fist.

pulls on one cable, linked to one phalanx interface attachment. Grooves in the phalanx attachments act as sheaths for cables to slide parallel to the longitudinal axes of the phalanges.

Each actuator is a DC motor-driven spooling mechanism, which spools the cable and pulls the corresponding phalanx interface attachment, thus, resulting in flexion of the associated finger joint. The motors (EC-max22, Maxon Motor, USA) provide tension to each cable through a timing belt-driven shaft that shares an axis with the spooling pulley. The motor controller boards (EPOS 24/2, Maxon Motor, USA) include onboard proportional integral differential control, which uses feedback from the motor encoders. These controllers were interfaced with a PC via USB, whereby actuation of the finger joints was commanded using position control (EPOS Studio 1.43, Maxon Motor, USA).

To provide passive return [12], extension springs with similar linear stiffness (180 N/mm) were attached on the dorsal side between distal and middle phalanx interface attachments, between middle and proximal phalanx attachments, and between proximal phalanx attachment and metacarpus attachment. The force exerted from the actuator induces flexion of one, two, or all finger joints to achieve the desired therapy posture, which in turn stretches the corresponding springs; upon gradual reduction of the actuator force to zero, the spring force returns the finger to its neutral resting posture (Fig. 3(*a*)). We considered this design, involving springs with the same stiffness, as design 1.

Differential Spring Stiffness Concept. Pathological finger joints are typically stiffer than normal healthy joints due to joint deformities and tendon adhesions; therefore, a larger external force is often necessary to move these joints into a desired flexion angle as compared to normal joints [2]. Based on this mechanism, it is possible to make a particular joint move under a certain level of applied force by varying the stiffness of the joint. Thus, we modified the design using a differential spring stiffness concept, such that we can dictate the sequence in which the finger joints move and achieve the desired therapy posture. The sequence, in the order of increasing stiffness, is DIP, PIP, and MCP. The DIP joint was made the least stiff so that it will flex first upon cable actuation. The PIP joint was made relatively stiffer so that it will flex right after the DIP joint completes its flexion. Finally, the MCP joint will be made the stiffest such that it flexes last in the sequence. This differential stiffness configuration was implemented using extension springs of different stiffness instead of the same stiffness as implemented in design 1. The appropriate spring stiffness used for the DIP, PIP, and MCP joints are 180, 240, and 590 N/m, respectively. We considered this design, involving springs with different stiffnesses, as design 2.

Actuator-Spring Mechanism State Diagrams. For design 1, the actuator-spring mechanism is implemented with an actuator-spring pair for each joint (M—MCP, P—PIP, D—DIP). By actuating the M-cable, P-cable or D-cable, the end-states will likely be the table top, straight fist, and fist therapy postures, respectively. Upon deactivation of the actuator through gradual reduction of the actuator force to zero, the passive springs should return the finger into the initial resting state (Fig. 3(*a*)).

In design 2, with springs of different stiffnesses, actuation of the M-cable will stretch the M-spring and likely give the end-state of table top posture. Actuation of the P-cable will stretch the P-spring first and subject the finger into the state of PIP blocking posture. The same actuation will subsequently stretch the M-spring, bringing the end-state into the straight fist posture. Actuation of the D-cable will stretch the D-spring first and achieve the state of DIP blocking posture. When the P-spring is stretched next, the state will likely be the hook fist posture. Finally, with the M-spring stretched, the end state will become the fist posture. Upon deactivation of the corresponding actuator through gradual reduction of the actuator force to zero, the springs will provide passive return, moving the finger joints back to the neutral resting state (Fig. 3(*b*)).

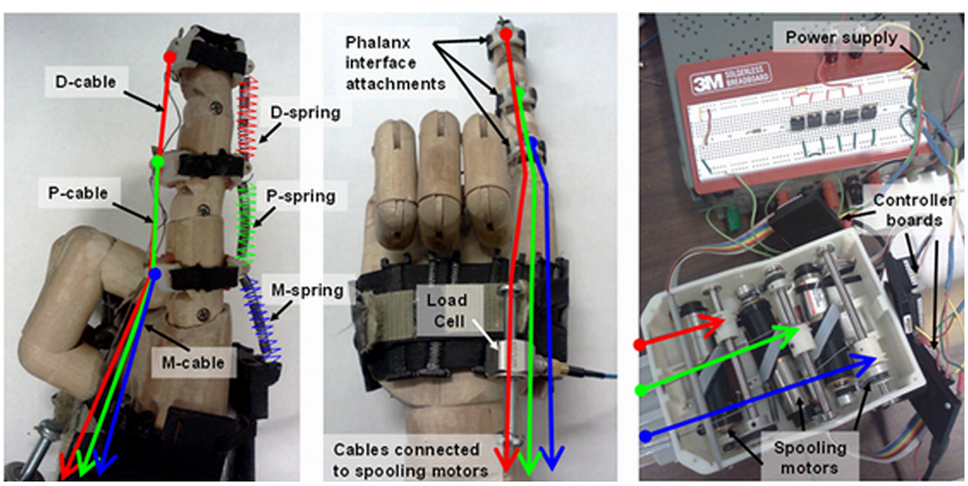

Fig. 2 Layout of the finger therapy exercise device donned on the index finger of a model hand. The device comprises of phalanx attachment interfaces, connected by cables on the palmar side to spooling actuators. On the dorsal side, the interfaces are linked by extension springs to provide passive return to the finger joints.

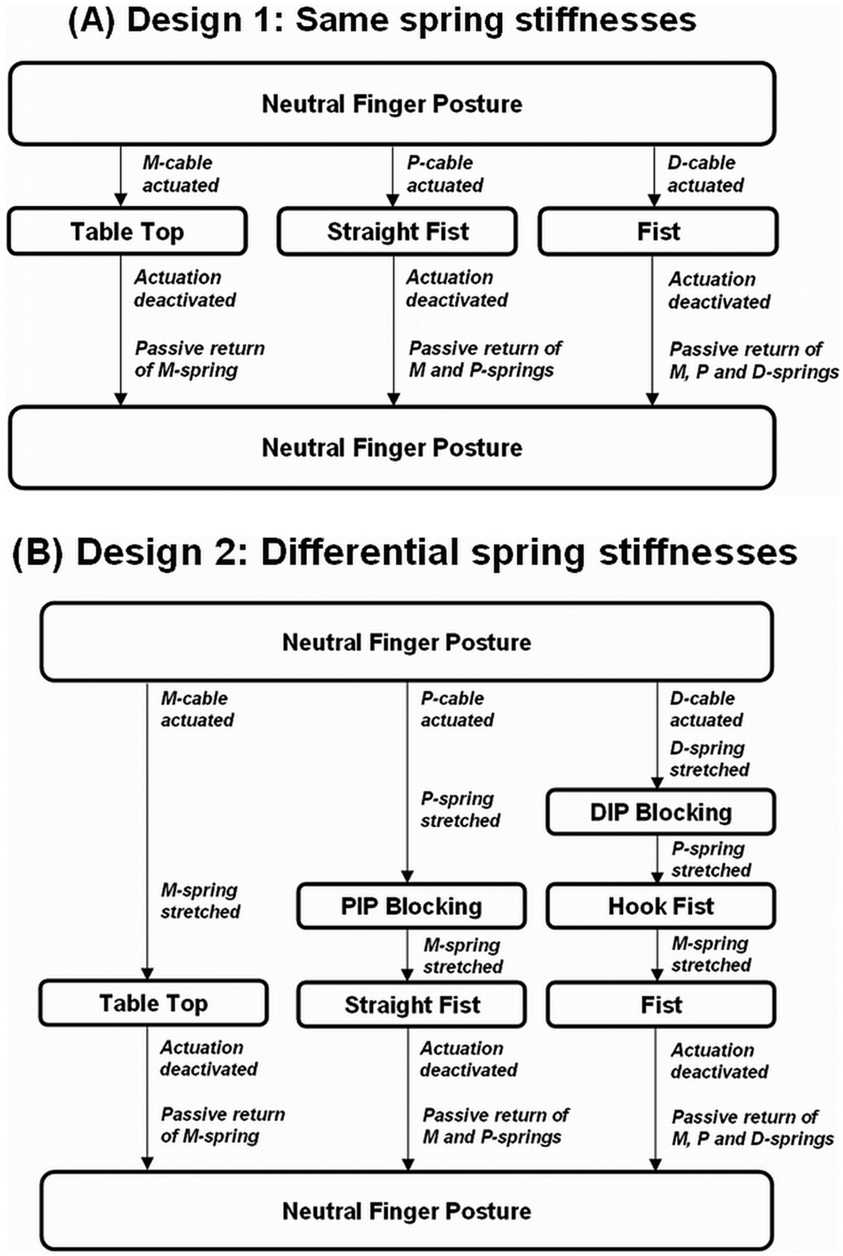

Fig. 3 State diagrams of (*a*) design 1 (same spring stiffnesses) and (*b*) design 2 (differential spring stiffnesses)

Device Evaluation. Therapy exercises were performed by moving finger from resting extended posture into each therapy posture by actuating the M-, P-, and D-cables, which in turn moves the cables linking to distal, middle, and proximal phalanges, respectively. Upon achieving desired posture, the cable actuation was deactivated by gradually reducing the actuator force to zero, and the springs steadily returned the finger to resting posture. For design 1, the table top, straight fist, and fist therapy exercises were performed. For design 2, the table top, PIP blocking, straight fist, DIP blocking, hook fist, and fist therapy exercises were performed. Each exercise was repeated six times, in which the joint angles were measured in the first three trials using a goniometer while the cable tension was measured in the last three trials using a load cell (9212, Kistler).

During joint-angle measurement trials, for design 1, the table top, straight fist, and fist therapy exercises were divided in three, four, and five intervals, respectively; for design 2, the table top, PIP blocking, straight fist, DIP blocking, hook fist, and fist therapy exercises were divided into three, three, four, three, six, and eight intervals, respectively. These intervals were designated based on the required command signal given to the motor to achieve the final therapy posture. For every exercise, the joint angles of the resting finger posture were first measured and subsequently after every interval, the cable actuation was paused and the joint angles were measured. For the cable-tension measurement trials, the cable actuation was not paused and the cable tension data was collected at a sampling rate of 30 Hz.

3 Results

For each exercise, the device was able to move the finger through the entire exercise motion for all six trials.

Design 1: Same Spring Stiffnesses. Actuation of the M-cable, attached to the proximal phalanx, substantially increased the MCP joint flexion angle, while leaving the DIP and PIP joints largely unaffected (Fig. 4(*a*)). A maximum cable force of 5.7 ± 0.2 N was required to attain the final posture, which was representative of a table top posture (Table 1). Deactivation of the actuator pulling M-cable allowed the passive M-spring to return the MCP joint back to the initial neutral posture.

Actuation of the P-cable, attached to the middle phalanx, increased the flexion angles of the PIP and MCP joints (Fig. 4(*b*) and Table 1); the cable actuation did not affect the DIP joint substantially. A maximum cable force of 10.9 ± 0.2 N was needed to achieve the final straight fist posture. Deactivation of the actuator pulling P-cable returned the PIP and MCP joints to the resting posture.

Actuation of the D-cable, connected to the distal phalanx, progressively increased the DIP, PIP, and MCP joint flexion angles (Fig. 4(*c*) and Table 1). A maximum cable force of 12.4 ± 0.2 N was necessary to move the finger into the final fist posture. Upon deactivation of the actuator pulling D-cable, all the joints returned to the resting posture.

Design 2: Different Spring Stiffnesses. Actuation of the M-cable, attached to the proximal phalanx, substantially increased the MCP joint flexion angle (Fig. 5(*a*)) with small changes in DIP and PIP joint angles (Table 1). A maximum cable force of 18.4 ± 0.8 N was applied to attain the final posture, which was indicative of a table top posture. Deactivation of the actuator pulling M-cable enabled the passive M-spring to return the MCP joint back to the initial neutral posture.

Actuation of the P-cable, attached to the middle phalanx, considerably increased the PIP joint flexion angle (Fig. 5(*b*)) with slight changes in the DIP and MCP joint flexion angles (Table 1). This posture of PIP blocking was achieved with a maximum cable force of 5.2 ± 0.3 N. Further actuation of the P-cable up to a maximum cable force of 15.0 ± 0.4 N notably increased the MCP joint angle (Fig. 5(*c*)), with minor flexion angle changes at the DIP and PIP joints. This final posture resembled the straight fist. Deactivation of the actuator pulling P-cable permitted the passive P-spring to return both the PIP and MCP joints back to the initial neutral posture.

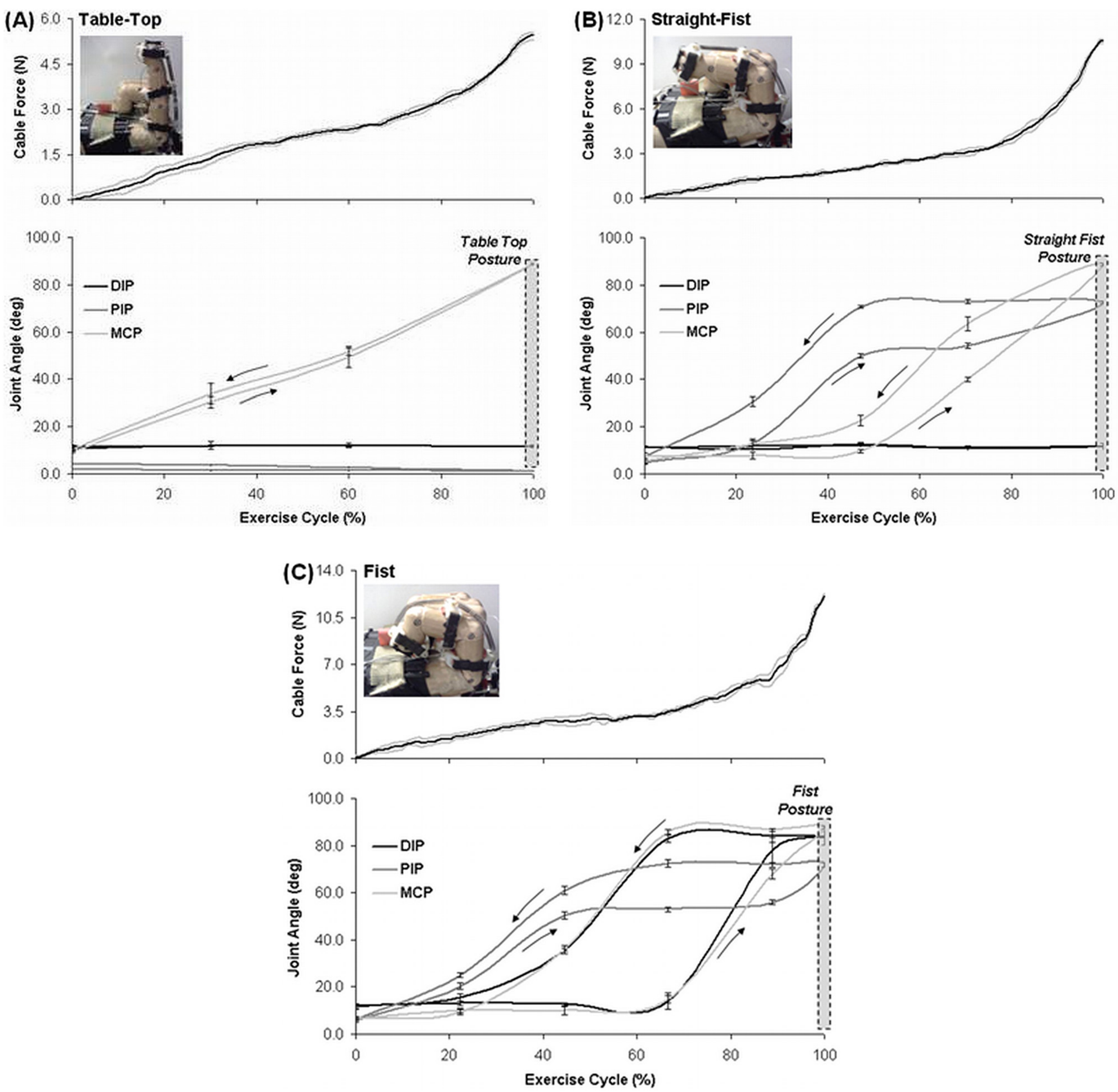

Fig. 4 Applied cable force profiles and corresponding joint angle profiles for the DIP, PIP, and MCP joints during execution of (*a*) table top, (*b*) straight fist, and (*c*) fist therapy exercises on the finger therapy exercise device with design 1 (same spring stiffnesses)

Table 1 Mean finger joint angles (standard deviation (SD)) for the DIP, PIP, and MCP joints during the neutral resting posture and the various desired postures achieved by the finger exercise device using both design 1 (same spring stiffnesses) and design 2 (differential spring stiffnesses)

Actuation	Posture	DIP angle (deg) (SD)	PIP angle (deg) (SD)	MCP angle (deg) (SD)
Design 1: same spring stiffnesses				
M-cable	*Neutral*	10.8 (0.3)	4.3 (0.6)	9.3 (0.6)
	Table top	11.7 (0.6)	1.2 (0.3)	**88.8 (0.3)**
P-cable	*Neutral*	11.5 (0.5)	5.0 (1.0)	5.7 (1.2)
	Straight fist	11.7 (1.5)	**72.7 (0.6)**	**88.7 (0.6)**
D-cable	*Neutral*	11.8 (1.0)	5.7 (0.6)	6.7 (0.6)
	Fist	**83.3 (3.1)**	**72.0 (1.0)**	**87.7 (0.6)**
Design 2: Differential Spring Stiffnesses				
M-cable	*Neutral*	5.3 (0.6)	5.7 (0.6)	6.2 (0.6)
	Table top	6.5 (0.9)	7.5 (0.5)	**80.2 (0.8)**
P-cable	*Neutral*	6.3 (1.2)	6.7 (0.6)	5.3 (0.6)
	PIP blocking	6.5 (0.5)	**79.3 (1.2)**	6.7 (0.6)
	Straight fist	6.7 (0.6)	**79.5 (1.8)**	**81.3 (1.2)**
D-cable	*Neutral*	7.3 (0.6)	5.0 (0.3)	5.3 (0.6)
	DIP blocking	**79.7 (0.6)**	8.3 (2.1)	6.3 (0.5)
	Hook fist	**80.7 (0.6)**	**79.8 (0.8)**	10.7 (0.6)
	Fist	**84.3 (2.1)**	**82.3 (1.5)**	**75.2 (0.8)**

Actuation of the D-cable, connected to distal phalanx, increased the DIP joint flexion angle (Fig. 5(*d*)) with little changes observed for the PIP and MCP joint flexion angles (Table 1). The posture represented the DIP blocking and required a maximum cable force of 1.6 ± 0.1 N. Further actuation of the D-cable with a maximum cable force of 6.4 ± 0.3 N moved the finger into hook fist posture (Fig. 5(*e*)), which saw an increase in flexion angle for the PIP joint and slight changes in DIP and MCP joint flexion angles. By raising the cable force to a maximum of 9.1 ± 0.4 N, the finger achieved the final fist posture (Fig. 5(*f*)). The MCP joint exhibited an increase in joint flexion angle, with small changes in the DIP and PIP joint flexion angles. Deactivation of the actuator pulling D-cable allowed the passive D-spring to return all the three joints back to the initial neutral posture.

4 Discussion

The purpose of this work was to design and evaluate a finger exercise device that is capable of recreating the therapy exercises, which are typically performed by occupational therapists. Previous studies have highlighted the benefits of physical therapy at preventing tendon adhesions during recovery postsurgery [13,14]. However, current hand CPM devices, such as the Sutter 5000 and the OttoBock WaveFlex, are not able to replicate physical therapy exercises well due to limitations in how they manipulate the individual finger joints.

For instance, the Sutter 5000 moves the proximal phalanx in a curved path of motion, in order to achieve MCP joint flexion only; the constraint of the Sutter 5000 is that it is unable to replicate the other standard therapy exercises normally assisted by physical therapists; therefore its clinical use is relatively limited to MCP joint rehabilitation [15]. In addition, the OttoBock WaveFlex applies a pushing force to the fingertips, resulting in a combined finger joint flexion motions of the hand and, thus, giving a final fist posture only. These combined motions do not address the individual joints independently, hence, neglecting the various finger joint postures that are present in standard therapy exercises.

The standard therapy exercises involve isolated finger joint motions that ensure every joint undergoes the full functional flexion ROM with the other finger joints maintained in an extended posture; these isolated joint motions are important in maintaining independent joint mobility and preventing joint stiffness due to the development of tendon adhesions and edema during postoperative healing of tissues [16,17]. Given that our designs can replicate all the standard therapy exercises, this capability allows the finger exercise device to be used in a wider range of clinical problems that necessitate multiple joint rehabilitation, as compared to current hand CPM devices. Although this study has achieved the objective of designing a finger exercise device and evaluating its ability to recreate standard therapy exercises, the efficacy of this device in the clinical setting is yet to be explored.

Our device, which is based on cable actuation at distal, middle, and proximal phalanges coupled with a spring return mechanism, allowed the finger to achieve the desired therapy postures, depending on the magnitude of cable force applied from the actuator. Upon actuator deactivation, the springs returned the finger to initial resting posture. Our finger exercise device, based on design 1 (same spring stiffness), is able to achieve the table top, straight fist, and fist postures.

Design 2 improves on the former design by introducing springs of different stiffnesses, in which the D-spring has the lowest stiffness, followed by the P-spring with a relatively higher stiffness, and finally the M-spring with the greatest stiffness. Design 2 demonstrated the capability to recreate all the physical therapy exercises, including DIP blocking, PIP blocking, and hook fist postures, using a simplified actuator-spring mechanism that relies on differential spring stiffness. Giudice [18] reported that current hand CPM devices do not provide sufficient interphalangeal flexion. In the current work, we have demonstrated that the finger device, based on design 2, can encourage interphalangeal flexion by replicating physical therapy exercises, particularly DIP blocking and PIP blocking. Together with the other complex physical therapy exercises that this design can achieve, it is possible that the finger device will help in progressively augmenting postoperative ROM of each finger joint.

A limitation of the current work was that we had to measure joint angles and cable tension separately due to the limited capability of the goniometer to generate real-time readings. Therefore, we split the exercises into intervals such that we could pause the exercise after every interval to record the goniometer readings for each joint. These joint angle readings can then be plotted together to display the general kinematic trend of the model finger during exercise (Figs. 4 and 5). We also like to highlight that we found minimal variations in joint angles during the conduct of exercise between trials (Table 1). The purpose of measuring cable tension was to show that with a progressive increase in cable tension, it was possible to manipulate the model finger into various desired postures; there were also minimal variations in cable tension during the conduct of exercise between trials (Figs. 4 and 5). Considering that we did not modify the model finger or the exercise

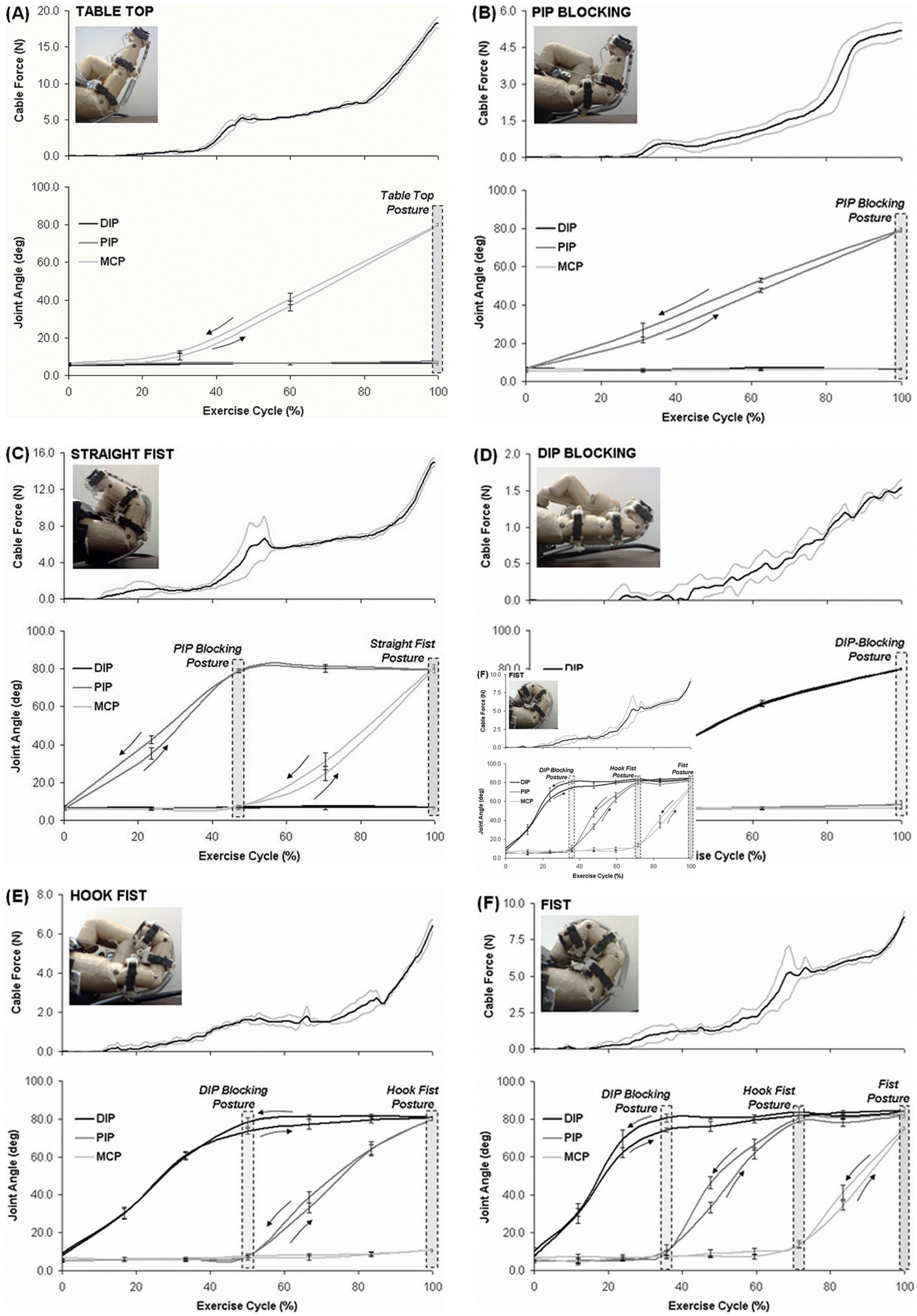

Fig. 5 Applied cable force profiles and corresponding joint angle profiles for the DIP, PIP, and MCP joints during execution of (*a*) table top, (*b*) PIP blocking, (*c*) straight fist, (*d*) DIP blocking, (*e*) hook fist, and (*f*) fist therapy exercises on the finger therapy exercise device with design 2 (differential spring stiffnesses)

device during the trials for each design, we expect the joint angles and cable tension to be reasonably similar between the six trials. It is important to note that the key aims of this study were to demonstrate that (1) a cable-actuated flexion and spring-return extension mechanism for the finger exercise device was capable of generating the desired joint angles necessary to recreate the therapy exercises, and (2) the desired postures for each of these exercises can be achieved by progressive increase in cable tension.

Another limitation was perhaps that the main focus of the study was to devise an actuation mechanism that can permit replication of the physical therapy exercises; therefore, there are nonactuation issues that have not been assessed, which may influence the user-friendliness of the device in the current state. One issue was the size of the actuation unit and off-board power supply, which limits the portability of the device; future works would consider the feasibility of implementing alternative means of actuation and power supply that allows the patient to use the device for a suitable length of time while at home. The advantage of portability for home use is likely the reduction in costs associated with hospital stays/visits and physiotherapy fees. Another issue was the ease and comfort in donning the device on a human finger/hand, which has been largely ignored in the current work, but will be considered in future iterations of the device. The presence of the exposed extension springs is also an important issue that needs to be addressed in future iterations of the device, as these exposed springs can potentially pinch the patient's skin and cause discomfort. A possible solution could be to fit the spring in a smooth elastic sheath to prevent contact between the spring and the patient's skin.

The actuator-spring designs developed in the current study can be implemented with future modifications of the finger exercise device, which will include reducing the size of the spooling actuation system, scaling up from a single finger device to a full hand rehabilitation device, including sensors to provide force and joint position feedback [19], and implementing safety mechanisms to protect repaired finger from excessive mechanical loading. In addition, the device should have an output display that provides information on time, joint angles, and force applied so as to allow therapists and surgeons to know the details of the CPM intervention and the corresponding results. Prospective functional testing of the device would be performed on human subjects to examine the efficacy of the design on actual human fingers.

Altogether, both design 1 (same spring stiffnesses) and design 2 (differential spring stiffnesses) eliminate the need for dorsal side actuators, which will likely reduce the overall bulk of the prospective device. Moreover, design 1 is able to recreate three therapy exercises (table top, straight fist, and fist); by using differential spring stiffness concept, design 2 is capable of replicating all six therapy exercises, which further include DIP blocking, PIP blocking, and hook fist. This work demonstrated the possibility of replicating finger therapy exercises using a cable-actuated flexion and spring-return extension design, which lays the groundwork for prospective finger exercise devices that can be donned on patients to assess the efficacy in postoperative joint rehabilitation.

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