Hand Spring Operated Movement Enhancer (HandSOME): A Portable, Passive Hand Exoskeleton for Stroke Rehabilitation

Elizabeth B. Brokaw, *Student Member, IEEE*, Iian Black, Rahsaan J. Holley, and Peter S. Lum, *Member, IEEE*

***Abstract*—Stroke patients often have flexor hypertonia and finger extensor weakness, which makes it difficult to open their affected hand for functional grasp. Because of this impairment, hand rehabilitation after stroke is essential for restoring functional independent lifestyles. The goal of this study is to develop a passive, lightweight, wearable device to assist with hand function during performance of activities of daily living. The device, Hand Spring Operated Movement Enhancer (HandSOME), assists with opening the patient's hand using a series of elastic cords that apply extension torques to the finger joints and compensates for the flexor hypertonia. Device design and calibration are described as well as functional and usability testing with stroke subjects with a wide range of hand impairments. In initial testing with eight stroke subjects with finger flexor hypertonia, use of the HandSOME significantly increased range of motion ($p < 0.001$) and functional ability ($p = 0.002$). There was some decrease in grip strength with the HandSOME device at the subject's ideal setting, however this was not statistically significant ($p = 0.167$) and did not seem to have a significant effect on function. Overall HandSOME shows promise as a training tool to facilitate repetitive task practice for improving hand function in stroke patients. HandSOME can be used as part of a home-based therapy program, or as an orthotic for replacing lost function.**

***Index Terms*—Function, hand, orthotic, rehabilitation, stroke.**

I. INTRODUCTION

STROKE has significant detrimental effects on motor function in the affected limbs. At three months poststroke, only 12% of stroke survivors report no difficulty with hand function and 38% of survivors reported major difficulty with hand function [1]. In stroke survivors, hand function is often lost due to flexor hypertonia (increased resistance to passive finger extension) and weakness in finger extensors. Unfortunately, reasonably precise motor function of the hand is necessary to perform activities of daily living (ADL) and thus stroke patients are often very dependent on compensatory strategies. The goal of this study was to develop a lightweight, passive, wearable device that assists with hand function during performance of ADL. The long term goal is to incorporate this device into a home-based training protocol for stroke survivors.

Repetitive use of the affected limb is an effective way to improve motor function [2]. As a result, many devices have been created to assist with hand movement and therapy. Available hand rehabilitation devices vary greatly in structure and mechanical properties but all have the general purpose of assisting with finger extension. The majority of devices currently on the market are active systems powered by electric or pneumatic motors. This leads to an increased device weight due to the inherently large weight of motors and power supplies relative to the weight of the human hand. These factors prevent current active systems from being used during ADL task training with stroke survivors, where proximal arm weakness is common. Many of these actively actuated devices utilize internal grasp structures [3]–[5], but this diminishes the possibility of use with real world objects, and can limit range of motion (ROM). Most of the current actively powered external grasp devices are exceedingly bulky and limit the type of grasp and hand orientation that can be used for task practice (see [6] for a complete review).

The passive (nonpowered) hand device field is relatively small, although several passive arm rehabilitation devices have been developed to aid with stroke recovery. These devices provide arm weight compensation using overhead pulley systems [7], [8], spring-based arm orthotics attached to wheelchairs [9], [10], and passive exoskeleton rehabilitation devices [11], [12]. The Saeboflex is an example of a passive hand rehabilitation device that has been successful in assisting with opening the grasp of stroke patients and is commonly used for tone management therapy [13]. However, this device is not intended for functional grasp of diverse objects, as it was designed only for picking up objects 3–4 in diameter and smaller objects cannot be grasped. The springs that are connected to the distal phalanx of each finger provide increasing force with increasing finger flexion, which makes it difficult to obtain and maintain full flexion even with low force springs, limiting ROM. Another passive hand device used for motor training is a cable driven orthotic by Fischer *et al.* [14]. However, this device requires the subject to use shoulder and elbow movement to assist with finger extension, which decreases the ability for normal movement kinematics in reach and grasp task training. This device has been extended to a motorized device controlled with

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E. B. Brokaw is with the National Rehabilitation Hospital, Washington DC 20010 USA and also with the Catholic University of America, Washington, DC 20064 USA (e-mail: elizabethbellb@ gmail.com).

I. Black and R. J. Holley are with the National Rehabilitation Hospital, Washington, DC 20010 USA (e-mail: iian.black@medstar.net; rahsaan.holley@medstar.net)

P. S. Lum is with the National Rehabilitation Hospital, Washington, DC 20010 USA, and also with the Catholic University of America, Washington, DC 20064 USA, and also with the Veterans Affairs Medical Center, Washington DC 20422 USA (e-mail: lum@cua.edu).

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voice, electromyography or manual input [15]. However, this change makes the device no longer passive, and the increased complexity and weight may affect arm transport and limit potential home use.

We have developed the Hand Spring Operated Movement Enabler (HandSOME), a passive, lightweight hand rehabilitation device that overcomes many of the limitations of current devices. HandSOME provides a large ROM and allows grasp of both small and large real world objects in even severely impaired subjects. This was accomplished by basing the design on the biomechanics of the hand after stroke. Kamper *et al.* examined the torque required to extend hypertonic finger joints and found a nearly linear relationship between metacarpophalangeal (MCP) joint extension angle and applied extension torque [16], [17]. They also found that stretching of the flexors elicited muscle activity in the paretic extensors. Therefore, we designed HandSOME to provide increasing extension assistance with increasing finger extension angle. The majority of stroke subjects have some residual ability to flex the fingers voluntarily, so assistance for flexion is generally not required.

HandSOME was designed only for the pinch-pad grasp, which brings the pads of the thumb and fingers together and contrasts with a power grasp where the thumb wraps around the fingers. Pinch-pad grasp can be used with many object shapes and sizes and is commonly used in ADL. The simplification to training a single gross grasp posture was motivated by the fact that stroke survivors often must rely on gross grasp for ADL due to loss of isolated individual finger movement, finger proprioception, and fine touch sensation [18]. Although different therapy methods may be needed to help retrain more dexterous movements, restoration of hand use in ADL through gross grasp training will likely impact the amount of use of the limb in everyday life, which may improve many stroke survivors' quality of life. The HandSOME device also utilizes a linkage between the finger and thumb actuating components to ensure proper inter-joint coordination in the grasp movement. This design will allow stroke survivors with lost independent joint control to obtain and hopefully retrain proper inter-joint coordination in grasp [19], [20].

These concepts of increasing assistive torque with increasing extension angle, potential for use in ADL, and the need for patient-initiated repetitive task practice inspired the HandSOME design. This device utilizes passive actuation via elastic cords to assist with finger and thumb extension. Passive actuation, as well as the use of light weight materials, allows for a wearable design, which increases portability. The HandSOME device was tested for comfort, the effect on ability to perform simple ADL, the effect on active ROM, and the potential negative effect on grip strength in individuals with various levels of hand impairment due to stroke.

II. HANDSOME DESIGN

HandSOME was designed to follow the normal kinematic trajectory of the hand during pinch-pad grasp, provide the assistance torque profile that best compensates for finger flexor hypertonia, and measure the angle of grasp using a small encoder (E4 Series, US Digital, Resolution 0.25°). A 4-bar linkage was designed to force the thumb and fingers to coordinate movement in the grasp. The HandSOME design uses elastic cords as springs to assist with finger and thumb extension, and provide assistance profiles that emulate the torque versus extension angle profiles for passive movement reported by Kamper *et al.* [17]. Changes in the spring location and stiffness used allow the therapist to vary the assistance profile and magnitude. Although two design versions were used in stroke subject testing, the two designs were identical in terms of the critical features of the HandSOME. The finger-thumb linkage and the assistance torque profiles remained unchanged between versions. Version 2 decreased the weight and general profile of the device. This difference between versions 1 and 2 of the device did not affect performance of the study tasks because subjects were allowed to support the paretic arm with their other arm if needed. Therefore, test data from all subjects were grouped together for analysis. All images shown in this paper depict the second version of the device. Fig. 1 shows the latest completed design and the hand interface.

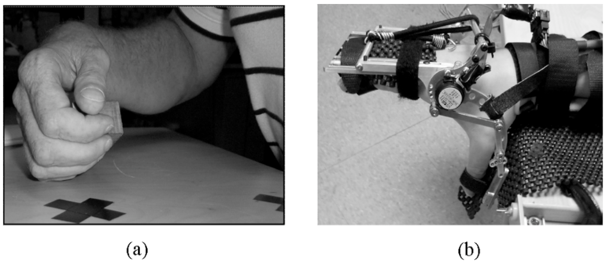
(a) (b)

Fig. 1. The left image shows a subject lifting the one inch block using a typical compensatory strategy. The subject was unable to pull his thumb around the block in grasp. The right image shows the HandSOME device fitted to a stroke subject with hypertonia.

The tested devices weigh 0.22 kg (version 1) and 0.128 kg (version 2). The device is able to accommodate a maximum finger length of 0.13 m and a maximum hand width of 0.1 m, with no minimum hand width or length. These hand measurements represent the 99th percentile for male hands [21].

Adjustable hard stops are used to control the ROM. This prevents the device from causing any harm to subjects who can not tolerate full ROM. Padding and support straps were added to the device for comfort and to maintain ideal positioning of the device on the back of the hand throughout the movement. The Velcro straps were positioned distally to prevent the fingers from curling around the straps. One strap was aligned with the distal phalanx of the pinky and another at the proximal interphalangeal joint (PIP) of the pointer finger. If needed, a third strap was used across the distal phalanges of the middle three digits. A single Velcro strap was used at the interphalangeal joint (IP) of the thumb. Therefore, the straps restricted movement of the thumb IP, finger DIP and finger PIP joints. The main movement is about the MCP of the fingers and the carpometacarpal joint (CMC) of the thumb. A wrist brace was used for subject testing to maintain neutral wrist posture in the device and to ensure proper orientation of the HandSOME device on the subject's hand. Various adjustments can be made to adapt for different size hands. The finger and thumb attachment points can be extended to match

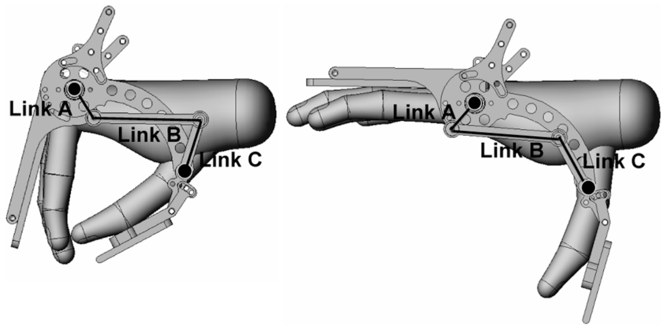

Fig. 2. The 4-bar linkage of HandSOME. The dark circles designate the ground points of the linkage (finger MCP and thumb CMC). The line between these two points (not shown) designates link G of the 4-bar linkage. The black lines are the links A, B, and C.

finger length and the thumb attachment component can be rotated to match the subject's thumb orientation.

A. Linkage Design

Since the device must be able to smoothly follow the movement of the human hand for comfort and proper retraining of normal grasp movement, the kinematics of the hand during the pad-pinch grasp were modeled. The hand movement was measured using an acoustic based three-dimensional motion tracking system (Zebris CMS-HLS). Markers were placed on the distal ends of the pointer finger and thumb as well as at the MCP joints. Five repetitions of this movement were recorded and the angles of rotation and coordination of the fingers and thumb were calculated. The finger MCP and thumb CMC joint positions were used as the rotation centers of the device. Analysis of the kinematics of several normal subjects showed synchronous movement coordination between the fingers and thumb with a range of motion of approximately 78° in the fingers and 39° at the thumb. To accommodate full passive ROM, the design specification for the linkage was defined as synchronous movement of 90° at the finger MCP and 45° at the thumb CMC.

A 4-bar linkage was designed to mimic the grasp motion and maintain the relationship between fingers and thumb that was modeled (Fig. 2). At first, a simplified three-position analysis was used to calculate a family of possible solutions that achieved the closed, half extended, and full extension hand positions. The ground link (Link G) was established between the finger MCP and thumb CMC. The length and direction of the link attached to the finger actuating component (Link A) was calculated by examining a grid of possible end points for Link A and the associated 4-bar design that achieved all three hand positions. For each design, the angles between the links were calculated and the set of solutions that did not approach singularities (0° or 180°) during the desired range of motion were chosen. This reduced the number of possible solutions to a manageable level. A mathematical model of the motion of each linkage was created and the link forces were calculated assuming the maximum design torque (4 Nm) was being applied by the user on the device (Matlab, Mathworks, Natick, MA). We then examined the remaining candidate linkage designs and chose the design that performed well in each of the following categories: avoiding singularities, minimizing link forces, minimizing link lengths, and not impeding grasp or view of the palm of the hand. The resulting 4-bar linkage is shown on the HandSOME device in Fig. 2. The actual ROM of the tested device was 90° at the finger MCP and 52° at the thumb CMC.

B. Torque Profile by Spring Location

The ability to control the applied torque profile is important for tailoring device assistance to the patient's ability. Our design goals were a torque magnitude greater than 4 Nm in the fully extended position, decreasing extension torque as the fingers flex to a closed position, and minimal spring length change over the ROM. 4 Nm was chosen based on pilot testing with a small sample of high tone patients; however higher peak torque values can be achieved simply by increasing spring stiffness by placing more elastic cords in parallel.

The linkage, spring properties, and the kinematics were input into a static model of the device to analyze a 2-D grid of possible locations for the spring ground and distal attachment locations. Examination of solutions determined that the most linear assistance profiles resulted from a spring path that goes through the center of rotation of the finger MCP when the hand is closed, thus completely eliminating the applied torque in this posture. To allow adjustment of the assistance profile for different patients, a series of ground point locations was selected that varied the amount of torque applied in the fully closed position. The system was then tuned for spring constant, spring rest length, and distal spring attachment point. This tuning involved examination of the torque assistance profiles with each possible design, with the goal of selecting spring characteristics that yielded an approximately linear torque assistance profile.

The final design is shown is Fig. 3. The ground point of the spring is located at the end of a lever arm that can be rotated to change the assistance profile. When the lever arm is in its normal position, the spring path goes through the center of rotation of the finger MCP when the hand is in full finger flexion (0° of finger extension). Theta is defined as the angle of the lever arm relative to this normal position. By rotating the lever arm away from this normal position, the therapist is able to change the shape of the assistance profile and increase the amount of assistance applied in the fully closed position. This allows individuals with no extension ability to use the device by simply relaxing their hand, causing the device to open their hand for them, whereas the $\mathrm{Theta} = 0$ setting will require some ability to extend volitionally from the fully closed position. The different torque profiles theoretically available are also shown in Fig. 3.

These diverse profiles can be used to match the tone profile of the subject, which will maximize the subject's range of motion and grip strength in the device. The actual torque profile was measured by attaching a force/torque sensor (Model: 67M25A, JR3 Inc., Woodland, CA) to the device and measuring the torque required to slowly open and close the device (no hand in device). The measured profiles were very similar to the theoretical calculations. We calculated the error between theoretical and experimentally measured torque profiles and found that with five springs attached, the average error across the full ROM of the device was 0.007 Nm for $\mathrm{Theta} = 0\ \mathrm{deg}$, and 0.036 Nm for

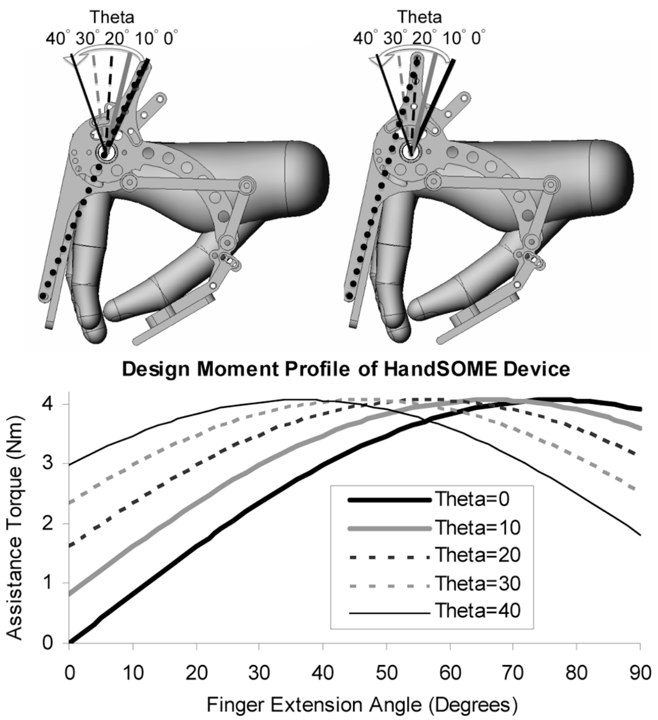

Fig. 3. The top images show the possible Theta settings for the HandSOME device, which determines the spring line of action. The images show the device at 0° of finger extension. At $\mathrm{Theta} = 0$ (top left image) the elastic cord line of action, as shown with the black dotted line, is directly through the center of rotation of the MCP when the device is in the fully flexed position and no assistance torque is applied. The other Theta settings are defined as an angle relative to the $\mathrm{Theta} = 0$ line of action. The elastic cord line of action for $\mathrm{Theta} = 20$ is shown in the top right image. The bottom plot shows the torque profiles corresponding with the different Theta settings.

$\mathrm{Theta} = 10\ \mathrm{deg}$. Using the same method without any springs attached, friction of the device was measured and found to be mostly constant through the device ROM with a maximum value of 0.038 Nm.

C. Elastic Cord Choice

The choices of spring attachment points were affected by the maximum extension ratios (the max spring length divided by the initial length) and spring constant (k) values of the potential actuators. Elastic cords were chosen instead of metal springs due to their higher extension ratios. Even with elastic cords, their limited extension ratios caused the peak of the torque profile to be moved to a more flexed position than the desired fully extended angle. The chosen elastic cords (Joubert 10-in Mini Bungee, $k = 74.6\ \mathrm{N/m}$) are easily attached to HandSOME and stiffness can be increased by simply adding more cords in parallel.

III. HANDSOME TESTING

The goal of this testing was to examine comfort, patient acceptance, and functional use of the device in subjects with severe to moderate hand impairment. Tests examined the ability of the device to increase ROM, improve performance in functional activities as measured by a block lifting task, and the effect of the device on the subject's grip strength. Inclusion criteria were a clinical diagnosis of stroke, elevated tone in the fingers, and absence of pain in the hand/wrist area. Eight stroke subjects were tested and their general information is shown in Table I. The clinical measurements were done before device testing by a trained occupational therapist. Upper extremity movement impairments at the shoulder, elbow, wrist, and fingers were evaluated with the Fugl–Meyer Assessment [22]. It scores reflexes and the ability to perform several simple movements and tasks on a three-point scale. A maximum summed score of 66 indicates no impairment. Muscle tone was measured in the finger flexors with the Modified Ashworth Scale [23]. The Ashworth is a five-point rating scale for measuring muscle tone, with ratings of 0 for no increase in tone up to a score of 4 for a rigid limb. All testing was approved by the MedStar Health Human Subjects Institutional Review Board. Due to the exploratory nature of this study, there was no correction for multiple statistical tests on the data collected.

TABLE I
SUMMARY OF SUBJECT CHARACTERISTICS

Subject #	1	2	3	4	5	6	7	8
Gender	F	M	F	M	F	F	M	M
Affected Hand	L	L	L	L	R	R	R	L
Time Post Stroke (yrs)	6	2	1	1	3.5	5.5	0.4	0.17
Ashworth, Finger Flexors (0-4) [23]	1+	1+	1+	2	1+	2	1+	2
Fugl-Meyer Upper Extremity (0-66) [22]	28	15	5	19	43	37	16	24

F=Female M=Male L=Left R=Right

A. Biomechanical Tone Examination

Characterization of hypertonia can be difficult due to the highly variable nature of the hyperactivity of the finger flexors. In order to get a general idea of the magnitude and profile of the subject's tone, the following experiment was performed before device testing. A force-torque sensor (Model: 67M25A, JR3 Inc.) was attached to HandSOME at a known distance from the finger component's center of rotation. The subjects were fitted into the device without springs attached and told to relax their hand while the researcher moved the subject's hand through their comfortable ROM three times at approximately 5°/s. The friction and gravity torques from the device during movement were subtracted from the measured torque profile.

B. Selecting Ideal Spring Settings and ROM

The following procedure was used to determine the ideal spring settings for each subject. To determine the best match to the subject's tone profile, three different torque profile settings were tested for each subject: $\mathrm{Theta} = 0°$, 20°, and 40° for the first version of the device and $\mathrm{Theta} = 0°$, 10°, and 20° for the second version of the device. The $\mathrm{Theta} = 30°$ and 40° settings were eliminated in the second version of the device since initial subject trials indicated there was no need for these extreme settings. The patient was asked to extend and flex their hand in the device three times at their own pace to obtain the unassisted free ROM. The subject was then asked to relax their hand and springs were then added until the patient's hand was in full extension. Again, the patient was asked to close and open his or her hand three times. These angles were recorded to determine the subject's maximum range of motion and movement profiles. The same fitting and testing procedure was used with each Theta setting. The Theta setting with the smallest number of springs and largest consistent range of motion was used in the functional testing as the ideal HandSOME setting for that subject. Paired t-tests were performed on ROM and peak movement velocity with and without spring assistance from HandSOME.

C. Functional Testing

The HandSOME device's capacity to increase performance of functional activities was measured in a task modeled after the Box-and-Blocks task [24]. Subjects were asked to move his or her hand from a start position to a block, lift the block off the table about 3-in and then put it down again. Since lifting the object was meant to show that the subject had a firm grasp on the block and we did not want proximal arm weakness to affect the data, the subject was allowed to use their unaffected limb to assist with the lifting and transport process by supporting the paretic forearm if needed. The blocks used were all of equal height and length but varied in width from 1/2- to 4-in. The functional testing was performed with and without the device. Subjects were allowed to rest and stretch their hand as needed during testing outside of HandSOME, but stretching was not allowed during testing inside of HandSOME. The time required to complete each task was recorded with a stopwatch to get a general measure of ease of movement. Stopping to stretch the hand was considered the end of an attempt and not included in the time recording. Subjects were informed that they did not need to rush, the pacing of movement was their choice, and that the time was only being recorded to compare between the hand alone and HandSOME trials. Functional testing of the hand alone was performed first to avoid potential increased hypertonia from repeated effort over the course of the test session. This functional testing was performed after the ROM testing, which determined the ideal HandSOME setting. Paired t-tests were performed on the largest block that could be lifted with and without HandSOME.

D. Grip Strength Testing

One potential concern with the HandSOME design is that the subject's grasp force may be decreased by the springs. This was tested by asking the subject to grasp a force sensor as strongly as possible for two seconds and then relax for three seconds (grip aperture $= 0.04$ m). Since the subject's hand is not completely closed, the springs are providing an extension torque to the fingers as they squeeze the sensor. This procedure was repeated three times with the subjects in the HandSOME device, first without spring assistance, and then again at their ideal spring settings. Paired t-tests were performed on peak grip force with and without HandSOME.

IV. RESULTS

Eight stroke subjects with a relatively wide range of functional ability were tested. The subject feedback on the HandSOME device was positive. Subjects commented that the device was generally comfortable and did not have any pressure points. Most of the subjects reported that they would be interested in using the device at home. The first four subjects were tested with version 1 of the HandSOME device [25]. Some of these subjects reported some difficulty in arm transport due to shoulder weakness and the device's weight. This problem was addressed in version 2 of the device and no subjects using this version reported added difficulty with arm transport. The major difference between the two versions of the device is weight, which should not have a significant effect on testing since subjects were allowed to use their unaffected arm to assist with transport of the objects in functional testing. Therefore data from both devices were collapsed for group analysis.

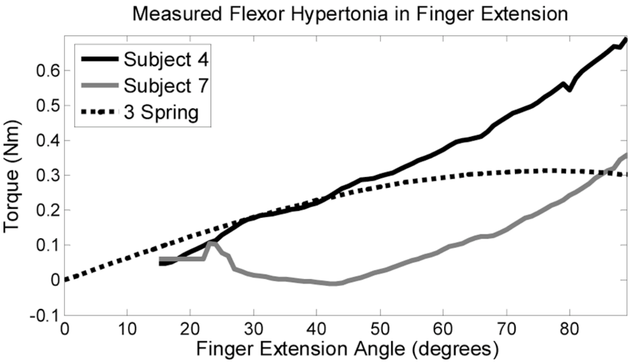

Fig. 4. Tone data of two subjects who used the three spring setting. Some subjects showed good matching of tone and assistance torque at maximum extension, while other subjects did not.

Maximum measured hypertonia varied between 0.2 and 0.8 Nm across subjects. The mean tone profile for all the subjects linearly increased with finger extension angle with an R-square value of 0.95. The resting hand posture was often not the fully flexed position (defined as 0 degrees-of-extension), so many of the tone profiles begin at around 20 degrees-of-extension. Fig. 4 shows the tone of two subjects who used an ideal spring setting of three springs. The figure shows that while one subject had a good match between tone and assistance torque at full extension, the other subject did not, possibly due to changes in tone over the course of the test session. In half of the subjects, the tone and assistance levels matched at full extension, which was the goal of the fitting procedure.

$\mathrm{Theta} = 0°$ was the ideal setting for 7 out of 8 subjects since they were able to move out of the fully flexed position, and had the lowest required spring force at this setting. The optimal setting for subject 7 was the $\mathrm{Theta} = 10°$ position. Although this subject had a slight amount of volitional extension, in ROM testing his movement was not consistent and he would occasionally get stuck in the full flexion position with the $\mathrm{Theta} = 0°$ setting. The $\mathrm{Theta} = 10°$ setting allowed consistent volitional extension away from the fully flexed position. Across all subjects, the optimal spring stiffness settings ranged from 2 to 5 springs. For two springs and $\mathrm{Theta} = 0$, the applied torque was 0 Nm with the hand closed and increased up to 0.2 Nm with the hand fully extended. For five springs and $\mathrm{Theta} = 0$, the extension torque at full extension was 0.5 Nm.

The active ROM increased with use of HandSOME ($p < 0.001$). All subjects had increased maximum ROM (max extension angle—min extension angle) with the HandSOME device,

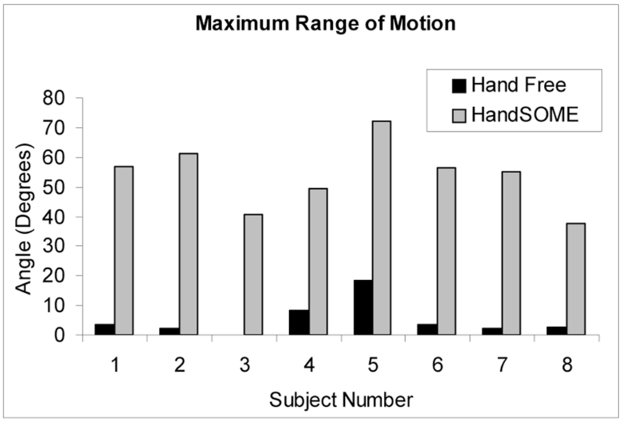

Fig. 5. Maximum range of motion (max extension angle—min extension angle) of the fingers with and without spring assistance from the HandSOME device. No ROM is shown for subject 3 in the hand free condition since the subject could not produce any finger extension.

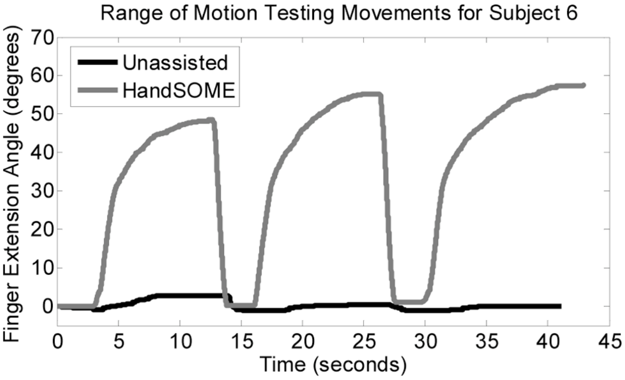

Fig. 6. Subject 6's movements in the HandSOME device with and without assistance from the HandSOME device. The other subjects had similar profiles in HandSOME, although the unassisted movements were sometimes much less consistent, with the three attempts resulting in only a single movement.

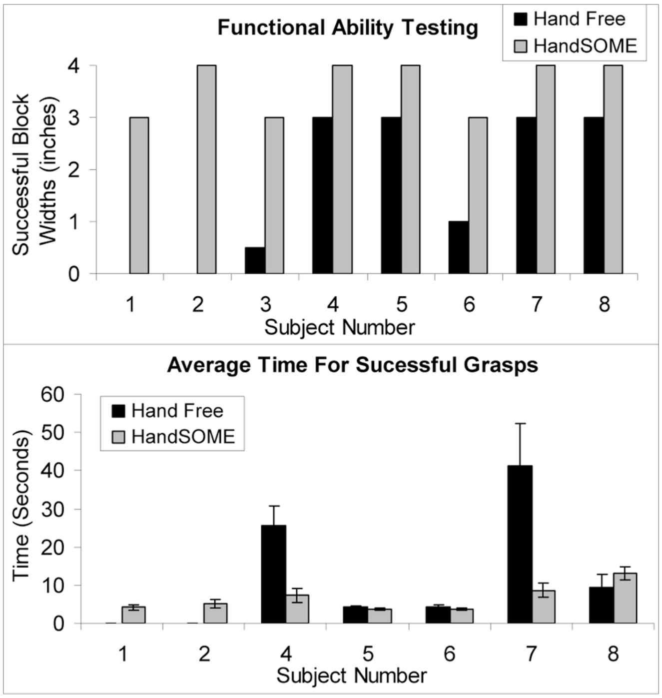

Fig. 7. The top panel shows the largest successfully lifted block width with and without HandSOME. All smaller blocks were successfully lifted in each case. The panel on the bottom shows the average self-paced time for a successfully lifted block with standard error bars. Subject 3 is not included in the lower plot due to lost timing data. Subjects 1 and 2 do not have time data in the Hand Free condition because they did not perform any successful lifts.

with an average increase of 48.7 ± 1.0 degrees-of-extension with the ideal HandSOME device settings as compared to the unassisted hand free condition (Fig. 5).

Subjects produced smooth movements in the device both in flexion and extension although the time for the extension movement was much larger than for flexion. In flexion, subjects showed a significant $(p = 0.004)$ peak velocity increase from 26.9 ± 13.9 $(\mathrm{mean} \pm \mathrm{SEM})$ degrees per second with the unassisted hand to 93.1 ± 24.76 degrees per second with the HandSOME device. Velocity in extension also increased from 11.3 ± 4.45 degrees per second with the unassisted hand to 59.4 ± 22.34 degrees per second with the HandSOME device, and this difference approached significance $(p = 0.053)$. Fig. 6 shows the ROM data of a single representative subject.

The goal of the block lifting task was to determine if using HandSOME increased the size of the largest object that could be lifted while not impairing the ability to lift smaller objects that subjects could already lift unassisted. Group analysis found that using the HandSOME device increased the size of the largest block that could be lifted $(p = 0.002)$. All subjects had improvements in the functional block testing with the HandSOME device. Fig. 7 displays movement times and the largest successfully lifted block width for each subject with and without the HandSOME device. In all cases, subjects were successful in lifting all blocks that were smaller than the largest lifted block. For example, subject 1 could not lift any of the blocks unassisted, but lifted all blocks from 1/2-in up to 3-in with HandSOME. There was little difference between hand free and HandSOME testing in terms of the average time for a successful lift in subjects 5, 6, and 8. The time data for subject 3 was lost. However, subjects 4 and 7 had the largest movement times in the hand free condition and had dramatic reductions in movement time when assisted by HandSOME. Subject 4's movement time improved from 25.6 to 7.3 s with HandSOME, while subject 7's movement time went from an average time of 41.1 s to 8.6 s per block. Since the subjects were told to move at their own pace, the large change in movement time showed that in these two subjects, the tasks were generally easier with the HandSOME device.

Grip strength was decreased when using the HandSOME, but this reduction was not statistically significant $(p = 0.17)$. On average the subjects lost 3.7 N of grip force, with an average grip strength of 29.9 ± 1.9 N for hand alone, and 26.2 ± 1.8 N with the HandSOME. This decrease in grip force was comparable to what would be predicted by calculating the extension torque applied to the hand by the springs. The aperture during testing corresponded to approximately 30 degrees-of-extension, which puts the extension torque at 0.12 Nm (two springs), 0.18 Nm (three springs), 0.24 Nm (four springs), and 0.30 Nm (five springs) for $\mathrm{Theta} = 0$. For the one subject who used three springs and $\mathrm{Theta} = 10\ \mathrm{deg}$, the torque was 0.23 Nm. Assuming an approximate finger length of 0.09 m, the average force lost from the springs would be 3.83 N.

V. DISCUSSION

Although all subjects had a large comfortable range of motion with HandSOME, no subject attained 90° of MCP extension as was the goal when determining the number of springs during fitting. This was most likely due to increased hypertonia after a period of hand use. Rapid changes in tone levels could also explain why hypertonia measurements at full extension matched assistance torque for only half of the subjects. Tone could have decreased due to the stretches performed during the tone measurements, or increased due to the unassisted range of motion testing. Although springs could be added or removed as needed to compensate for these fluctuations, we elected to not adjust the number of springs after the initial fitting period to properly evaluate the fitting procedure we developed.

In the unassisted hand functional testing, subjects were allowed to compensate by pushing their hands over the blocks, which allowed some subjects with little or no volitional extension to grasp some of the smaller blocks. Although this created some discrepancies between the ROM data and the implied ROM of the functional testing, this method allowed for the most realistic evaluation of real world use of the affected hand. The subjects did not use this compensation method with the HandSOME device.

Some decrease in grip force was expected since the hand was not fully closed during grip testing, resulting in extension torques from the springs that would reduce grip force. The estimated theoretical lost force (3.83 N) was approximately equal to the measured force lost (3.7 N). However, three subjects actually showed increased grip strength with the HandSOME, which could be due to a better hand posture when the springs were applied. Nevertheless, decreased grip force did not affect the functional lifting task with HandSOME, as in all cases a failed attempt was due to inability to open the hand wide enough for the object and not due to difficulty maintaining a large enough grip force.

The HandSOME facilitates practice of functional reach and grasp tasks. However there is debate over whether this functional approach is superior to impairment-based training that focuses on components of a functional task, such as joint ROM exercises. Therapists currently emphasize functional training for many types of stroke patients, and this practice is supported by recent reviews [26], [27]. However a study by Krebs *et al.* showed that training of robot-assisted reaching movements produced greater reductions in shoulder-elbow impairment than a time-matched dose of functional robotic training consisting of combined reach and grasp tasks [28]. A contributing factor to this result might have been the smaller number of total reaching repetitions in the functional protocol because of the time required for the grasping movements. The authors also hypothesized that the subject's focus on grasp and release in the combined functional task diverted attention from the arm transport aspect of this task. Another study showed that when training stroke subjects on a pointing task, outcomes were better when subjects were given feedback on shoulder and elbow kinematics rather than feedback on endpoint errors [29]. This further supports the advantages of focusing attention on the components of a functional task.

Despite this clinical evidence in favor of impairment-based approaches, there is physiological evidence in favor of training a coordinated reach and grasp task. While some studies support the independent visuomotor channel hypothesis of different control pathways for arm transport, hand orientation and grasp [30], [31], several other studies have shown a coordination between grasp aperture and arm transport in neurologically normal subjects [32], [33] that is impaired after stroke [34]. Primate and brain imaging studies in humans are beginning to isolate the neural substrate that underlies this coordination [35], [36]. The existence of these neural pathways suggests training of coordinated arm transport and grasp might be more beneficial than grasp training alone. Furthermore, integration of grasp practice into the context of a functional ADL may be more motivating for the subject than repetitive grasp training alone. Further research on the optimal paradigm for arm and hand training is needed.

Passive, lightweight hand rehabilitation devices could prove beneficial to the rehabilitation process because they can be worn during ADL with minimal weight effects on arm transport. None of the subjects tested with the lighter version had problems with the added weight. However, given that many patients have severe proximal arm weakness and fatigue quickly, further weight reductions may be required. Although this paper only presented the possible use of the HandSOME device for therapeutic intervention, the device could potentially also be used as an orthotic for replacement of functions that cannot be retrained. This might be particularly useful in patient populations with significant bilateral hand impairment, where use of an orthotic such as HandSOME might greatly improve functional independence.

Limitations of the device and the study should be noted. Since only extension assistance is provided, it is clear that subjects with severe weakness in flexors cannot use the device. Our convenience sample did not yield a subject with an Ashworth tone level greater than 2. It is possible HandSOME will not be effective in these high tone subjects. However, we surmise this will not be the case, as extension assistance can be easily increased by adding additional spring elements in parallel. Block lifting is a relatively limited representation of "functional testing" and in future studies, performance on standardized clinical evaluations such as the Box-and-Blocks should be tested. Currently, placing the subject's hand into the device is an intricate process requiring considerable skill on the part of the experimenter. Since one of the long term goals is use of HandSOME in a home training program, improvements are underway so that a subject can easily don the device on their own. Currently, the available assistance levels are too coarse to perfectly match the subject's tone profile. We are working on modifications to allow easy adjustment of assistance level in fine increments to motivate maximal effort on the part of the subject. We are also working on ways to accommodate a power grasp and a pinch-pad grasp in the same device to increase the repertoire of possible ADLs that can be performed with the device.

VI. CONCLUSION

HandSOME can assist stroke survivors with hypertonia to regain functional grasp ability. The newest version of the device has very low weight, which should allow for arm transport with the device and ADL use even in subjects with shoulder weakness. In summary, the general benefits of the device are: 1) passive, lightweight, wearable hand rehabilitation device, 2) small device profile with no internal grasp structures for use in ADL, 3) a linkage for improved coordination of the fingers and thumb, 4) allows for nearly full ROM in pinch-pad grasp, and 5) adjustable torque profile and magnitude to best match the subject's hypertonia for accurate and optimal compensation. Subjects showed large increases in active ROM with the device as well as increased ability for functional grasp of objects. This improved ability should help encourage stroke survivors to use the affected limb in everyday activities, which may lead to improvements in hand function without the device. Future efforts will examine the ability of stroke patients to independently don the device, develop a method for finer adjustment of assistance magnitudes, and explore the device's potential use in the home environment. For home use, we envision a training program based on a version of HandSOME that has a wireless sensor recording movement and a game interface to further motivate practice. Whether or not using the device provides added value over an equivalent amount of practice without the device is an empirical question that will have to be answered in future studies. However, given that the device can potentially be very inexpensive, justification for its use might be based solely on its role as a motivator for increasing home practice.

REFERENCES

[1] D. W. Duncan, R. K. Bode, S. M. Lai, and S. Perera, "Rasch analysis of a new stroke-specific outcome scale: The stroke impact scale," *Arch. Phys. Med. Rehabil.*, vol. 84, pp. 950–963, Jul. 2003.

[2] E. Taub, G. Uswatte, and T. Elbert T, "New treatments in neurorehabilitation founded on basic research," *Nat. Rev. Neurosci.*, vol. 3, no. 3, pp. 228–236, Mar. 2002.

[3] M. Bouzit, G. Burdea, G. Popescu, and R. Boian, "The Rutgers Master II—New design force-feedback glove," *IEEE/ASME Trans. Mechatron*, vol. 7, no. 2, pp. 256–263, Jun. 2002.

[4] L. Masia, H. I. Krebs, P. Cappa, and N. Hogan, "Design and characterization of hand module for whole-arm rehabilitation following stroke," *IEEE/ASME Trans. Mechatron.*, vol. 12, pp. 399–407, Aug. 2007.

[5] O. Lambercy, L. Dovat, R. Gassert, E. Burdet, C. L. Teo, and T. Milner, "A haptic knob for rehabilitation of hand function," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 3, pp. 356–366, Sep. 2007.

[6] S. Balasubramanian, J. Klein, and E. E. Burdet, "Robot-assisted rehabilitation of hand function," *Current Opin. Neurol.*, vol. 23, no. 6, pp. 661–670, 2010.

[7] A. Stienen, E. Hekman, G. Prange, M. Jannink, F. van der Helm, and H. van der Kooij, "Freebal: Design of a dedicated minimal weight-support system for upper-extremity rehabilitation," *ASME J. Med. Dev.*, vol. 3, no. 4, pp. 1–9, 2009.

[8] G. B. Prange, M. J. Jannink, A. H. Stienen, H. van der Kooij, M. J. Ijzerman, and H. J. Hermens, "Influence of gravity compensation on muscle activation patterns during different temporal phases of arm movements of stroke patients," *Neurorehabil. Neural Repair*, vol. 23, no. 5, pp. 478–485, Jun. 2009.

[9] J. L. Herder, N. Vrijlandt, T. Antonides, M. Cloosterman, and P. L. Mastenbroek, "Principle and design of a mobile arm support for people with muscular weakness," *J. Rehabil. Res. Develop.*, vol. 43, no. 5, pp. 591–604, Aug.–Sep. 2006.

[10] T. Rahman, W. Sample, R. Seliktar, M. T. Scavina, A. L. Clark, K. Moran, M. A. Alexander, and I. Alfred, "Design and testing of a functional arm orthosis in patients with neuromuscular disease," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 15, no. 2, pp. 244–251, Jun. 2007.

[11] S. J. Housman, K. M. Scott, and D. K. Reinkensmeyer, "A randomized controlled trial of gravity-supported, computer-enhanced arm exercise for individuals with severe hemiparesis," *Neurorehabil. Neural Repair*, vol. 23, no. 5, pp. 505–514, Jun. 2009.

[12] A. Stienen, E. Hekman, G. Prange, M. Jannink, A. Aalsma, F. van der Helm, and H. van der Kooij, "Dampace: Design of an exoskeleton for force-coordination training in upper-extremity rehabilitation," *ASME J. Med. Dev.*, vol. 3, no. 3, pp. 1–10, 2009.

[13] J. F. Farrell, H. B. Hoffman, J. L. Snyder, C. A. Giuliani, and R. W. Bohannon, "Orthotic aided training of the paretic upper limb in chronic stroke: Results of a phase 1 trial," *Neurorehabilitation*, vol. 22, no. 2, pp. 99–103, Jul. 2007.

[14] H. C. Fischer, K. Stubblefield, T. Kline, X. Luo, R. V. Kenyon, and D. G. Kamper, "Hand rehabilitation following stroke: A pilot study of assisted finger extension training in a virtual environment," *Topics Stroke Rehabil.*, vol. 12, no. 1, pp. 1–12, 2007.

[15] J. Ochoa, Y. J. D. Narasimhan, and D. G. Kamper, "Development of a portable actuated orthotic glove to facilitate gross extension of the digits for therapeutic training after stroke," in *Proc. IEEE Eng. Med. Biol. Soc. Conf.*, 2009, vol. 69, pp. 6918–6921.

[16] D. G. Kamper, R. L. Harvey, S. Suresh, and W. Z. Rymer, "Relative contributions of neural mechanisms versus muscle mechanics in promoting finger extension deficits following stroke," *Muscle Nerve*, vol. 28, pp. 309–318, 2003.

[17] D. G. Kamper and W. Z. Rymer, "Quantitative features of the stretch response of extrinsic finger muscles in hemiparetic stroke," *Muscle Nerve*, vol. 23, pp. 954–961, Jun. 2000.

[18] A. Welmer, L. W. Holmqvist, and D. K. Sommerfeld, "Limited fine hand use after stroke and its association with other disabilities," *J. Rehabil. Med.*, vol. 40, pp. 603–608, 2008.

[19] P. Raghavan, E. Petra, J. W. Krakauer, and A. M. Gordon, "Patterns of impairment in digit independence after subcortical stroke," *J. Neurophysiol.*, vol. 95, pp. 369–378, 2006.

[20] C. E. Lang and M. H. Schieber, "Reduced muscle selectivity during individuated finger movements in humans after damage to the motor cortex or corticospinal tract," *J. Neurophysiol.*, vol. 91, no. 4, pp. 1722–1733, 2004.

[21] S. N. Chengalur, S. H. Rodgers, and T. E. Bernard, *Kodak's Ergonomic Design for People at Work*, 2nd ed. New York: Wiley, pp. 48–49.

[22] A. Fugl-Meyer, L. Jääskö, I. Leyman, S. Olsson, and S. Steglind, "The post-stroke hemiplegic patient. 1. A method for evaluation of physical performance," *Scand. J. Rehabil. Med.*, vol. 7, no. 1, pp. 13–31, 1975.

[23] J. M. Gregson, M. Leathley, A. P. Moore, A. K. Sharma, T. L. Smith, and C. L. Watkins, "Reliability of the tone assessment scale and the modified Ashworth scale as clinical tools for assessing poststroke spasticity," *Arch. Phys. Med. Rehabil.*, vol. 80, no. 9, pp. 1013–1016, 1999.

[24] J. Desrosiers, G. Bravo, R. Hebert, E. Dutil, and L. Mercier, "Validation of the box and block test as a measure of dexterity of elderly people: Reliability, validity, and norms studies," *Arch. Phys. Med. Rehabil.*, vol. 75, no. 7, pp. 751–755, 1994.

[25] E. B. Brokaw, R. J. Holley, and P. S. Lum, "Hand spring operated movement enhancer (HandSOME) device for hand rehabilitation after stroke," in *Proc. IEEE Eng. Med. Biol. Soc. Conf.*, 2010, pp. 5867–5870.

[26] L. Oujamaa, I. Relave, J. Froger, D. Mottet, and J. Pelissier, "Rehabilitation of arm function after stroke. Literature review," *Ann. Phys. Rehabil. Med.*, vol. 52, no. 3, pp. 269–293, 2009.

[27] A. A. Timmermans, H. A. Seelen, R. D. Willmann, and H. Kingma, "Technology-assisted training of arm-hand skills in stroke: Concepts on reacquisition of motor control and therapist guidelines for rehabilitation technology design," *J. Neuroeng. Rehabil.*, vol. 6, pp. 1–1, 2009.

[28] H. I. Krebs, S. Mernoff, S. E. Fasoli, R. Hughes, J. Stein, and N. Hogan, "A comparison of functional and impairment-based robotic training in severe to moderate chronic stroke: A pilot study," *NeuroRehabilitation*, vol. 23, no. 1, pp. 81–87, 2008.

[29] M. C. Cirstea and M. F. Levin, "Improvement of arm movement patterns and endpoint control depends on type of feedback during practice in stroke survivors," *Neurorehabil. Neural Repair*, vol. 21, no. 5, pp. 398–411, 2007.

[30] J. Wang and G. E. Stelmach, "Coordination among the body segments during reach-to-grasp action involving the trunk," *Exp. Brain Res.*, vol. 123, no. 3, pp. 346–350, 1998.

[31] M. Jeannerod, "Intersegmental coordination during reaching at natural visual objects," in *In: Attention and Performance*, J. Long and B. A. Hillsdale, Eds. Mahwah, NJ: Erlbaum, 1981, pp. 153–168.

[32] Y. Paulignan, V. G. Frak, I. Toni, and M. Jeannerod, "Influence of object position and size on human prehension movements," *Exp. Brain Res.*, vol. 114, no. 2, pp. 226–234, 1997.

[33] R. G. Marteniuk, J. L. Leavitt, C. L. Mackenzie, and S. Athenes, "Functional relationships between grasp and transport components in a prehension task," *Human Movement Sci.*, vol. 9, no. 2, pp. 149–176, 1990.

[34] J. Tretriluxana, J. Gordon, B. E. Fisher, and C. J. Winstein, "Hemisphere specific impairments in reach-to-grasp control after stroke: Effects of object size," *Neurorehabil. Neural Repair*, vol. 23, no. 7, pp. 679–691, 2009.

[35] E. Stark, I. Asher, and M. Abeles, "Encoding of reach and grasp by single neurons in premotor cortex is independent of recording site," *J. Neurophysiol.*, vol. 97, no. 5, pp. 3351–3364, 2007.

[36] C. Cavina-Pratesi, S. Monaco, P. Fattori, C. Galletti, T. D. McAdam, D. J. Quinlan, M. A. Goodale, and J. C. Culham, "Functional magnetic resonance imaging reveals the neural substrates of arm transport and grip formation in reach-to-grasp actions in humans," *J. Neurosci.*, vol. 30, no. 31, pp. 10306–10323, 2010.

Elizabeth B. Brokaw (S'10) received the B.S. degree in biological resources engineering from the University of Maryland, College Park, in 2008, and the M.S. degree in biomedical engineering, in 2009, from The Catholic University of America, Washington, DC, where she is currently a Ph.D. candidate in the same program.

Iian Black received the B.S. degree in biomedical engineering from the University of California, Berkley, in 1996, and the M.S. degree in biomedical engineering from The Catholic University of America, Washington, DC, in 2004.

He is currently a Research Engineer at the National Rehabilitation Hospital, Washington, DC.

Rahsaan J. Holley received the B.S. degree in psychology from The City University of New York, Brooklyn College, in 1998, and the M.S. degree in occupational therapy from Columbia University, in 2000.

He is currently a Research Occupational Therapist at the National Rehabilitation Hospital, Washington, DC.

Peter S. Lum (M'09) received the B.S. degree in mechanical engineering from George Washington University, Washington, DC, in 1987, the M.S. degree in applied mechanics from the California Institute of Technology, Pasadena, in 1988, and the Ph.D. degree in bioengineering from a joint program between the University of California at San Francisco and Berkley, in 1993.

He is currently an Associate Professor in the Biomedical Engineering Department at The Catholic University of America, Washington, DC. He is also a Research Health Scientist at the Washington DC Veterans Affairs Medical Center and the Director of the Center for Applied Biomechanics and Rehabilitation Research (CABRR) at the National Rehabilitation Hospital, Washington, DC.