CRUX: a Compliant Robotic Upper-extremity eXosuit for lightweight, portable, multi-DoF muscular augmentation

Steven Lessard[1], Pattawong Pansodtee[1], Ash Robbins[1], Leya Breanna Baltaxe-Admony[1], James M Trombadore[1], Mircea Teodorescu[1], Adrian Agogino[2], and Sri Kurniawan[1,3]

***Abstract*— Wearable robots can potentially offer their users enhanced stability and strength. These augmentations are ideally designed to actuate harmoniously with the user's movements and provide extra force as needed. The creation of such robots, however, is particularly challenging due to the complexity of the underlying human body. In this paper, we present a compliant, robotic exosuit for upper-extremities called CRUX. This exosuit, inspired by tensegrity models of the human arm, features a lightweight (1.3 kg), flexible design for portability. We also show how CRUX maintains full flexibility of the upper-extremities for its users while providing multi-DoF augmentative strength to the major muscles of the arm, as evident by tracking the heart rate of an individual exercising said arm. Exosuits such as CRUX may be useful in physical therapy and in extreme environments where users are expected to exert their bodies to the fullest extent.**

I. INTRODUCTION

A. Bio-inspired Design

Through evolution, nature has slowly optimized the designs and functions of various organisms. For humans, this includes the movement and control of bilateral manipulators: the arms. This natural design has in turn inspired the development of similar man-made devices and robots to accomplish similar tasks performed by human arms.

The field of soft robotics features machines constructed out of "soft" materials, such as elastics and plastics. Soft materials are inherently compliant and resistant to external forces, allowing soft robots to function more similarly to the human body than rigid bodies. One branch of soft robotics is tensegrity robotics.

Tensegrity systems are hybrid soft-rigid structures. These compliant systems are made up of rigid compression elements suspended within a network of soft tensile elements. When a load is applied to a tensegrity structure, the forces are distributed throughout the entire system, preventing single points of failure [1]. Many similarities can be drawn between tensegrity structures and the musculoskeletal system of the human body. In the human body, rigid bones are typically held in place by tensile networks, including those formed by active tension elements (i.e. muscles) and passive tension elements (e.g. connective tissue such as tendons, ligaments, and fascia). As a result, tensegrity models of the human arm offer a useful perspective when designing human-oriented robots, such as exosuits.

*This work was supported by CITRIS

[1]Department of Computer Engineering, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA, USA [2]NASA Ames Dynamic Tensegrity Robotics Lab, Moffett Field, CA, USA [3]Department of Computational Media, University of California Santa Cruz, 1156 High Street, Santa Cruz, CA, USA slessard@ucsc.edu

Fig. 1. CRUX: a soft, lightweight ($1.3kg$), robotic exosuit for upper-extremity augmentation that does not significantly inhibit flexibility of its user.

Previous tensegrity manipulators have been created to exemplify these principles [2], [3], [4]. These manipulators illustrate the design of cable driven systems, which are similar to the human body - specifically the shoulder and elbow joints. They also illuminate actuation strategies and control considerations for these hybrid soft-rigid systems. Namely, these tensegrity joints created symmetrical passive compliance at equilibrium for withstanding external impacts. In human-interfacing devices, such as exosuits, this attribute is important for both the safety of the user and the integrity of the robot itself.

B. Exoskeletons and Exosuits

Exoskeletons and exosuits (i.e. "soft" exoskeletons) have been engineered for numerous purposes centering around the theme of assisting a human user. CAREX, the upper-extremity exoskeleton developed at Columbia University's ROAR Lab, uses a cable-threaded series of rings encircling the arm to train users according to a specific task, such as laproscopic surgery [5], [6].

Other exoskeletons and exosuits, such as those designed by the Wyss Institute at Harvard University and SUPERFlex Labs, provide mechanical strength for the sake of augmenting users. These lower-extremity exosuits use soft material to augment walking by applying a targeted boost of energy during the user's gait [7], [8]. The pneumatically driven exosuits from Tsagarakis et al. and commercial groups such as Roam of OtherLabs also promote compliant augmentation through soft structures [9], [10].

Augmentative exosuits for the upper-extremities have similar goals. One such exo-brace by Howe and Popovic et al. exhibits a single degree of freedom (DoF) shoulder actuator. This device uses online sensing to identify misalignments in user posture for the eventual purpose of portable, at-home rehabilitation [11]. This robot exhibits many of the paradigms central to soft robotics such as flexibility and lightweight construction. Despite only providing one degree of freedom, the novelty presented by this upper-body orthotics system serves as an important step for designing exosuits with greater capability and articulation. With one degree of freedom, users are constrained from fully articulating their joint as a healthy counterpart would, thus inhibiting proper movement and potentially preventing a full rehabilitation. To thoroughly augment a particular human joint, every degree of freedom naturally achievable by that joint must be represented in the rehabilitative robot.

The current research proposes a flexible multi-degree of freedom augmentation soft exoskeleton for the uppper extremity called Compliant Robotic Upper-extremity eXosuit (CRUX).

As a starting point we used the Arm26 OpenSim [12] simulation of an average size man flexing the right arm from relaxed position to full biceps curl. Figure I-B shows the simulation at 3 different time steps. Figure I-B shows the change in fiber length for different muscle groups (a) and the moment applied around the elbow joint. The authors note that the model exemplifies the antagonistic relationship between different muscle groups. While the length of the biceps (agonist muscle) fiber decreases as it contracts and the fiber length of the triceps (antagonist) increases as it is forced to relax. Additionally, the biceps and triceps create opposing moments around the elbow joint.

The goal of the proposed exosuit is to simultaneously augment the behavior of different muscle groups, including those corresponding to antagonistic pairs of muscles. We believe that a conformable augmentative exosuit for upper-extremity is a crucial step towards developing a robotic assistive technique for rehabilitation.

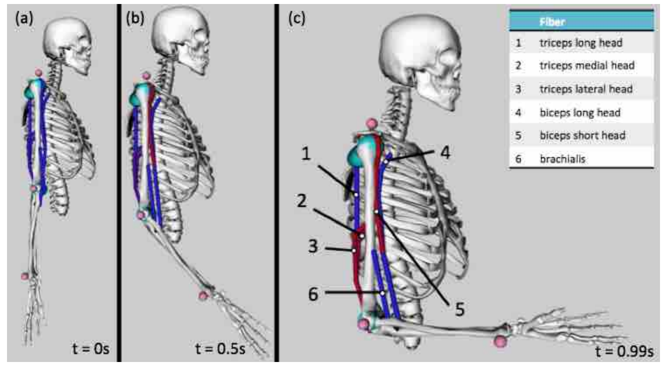
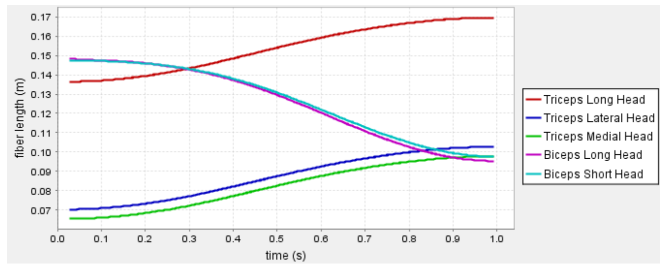
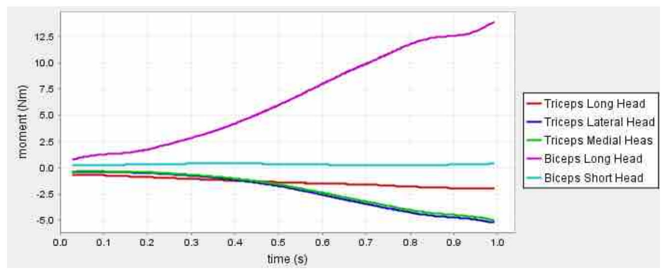


Fig. 2. OpenSim [12] simulation a flexing the arm from relaxed position to biceps curl for an average sized man.



(a) Fiber length



(b) Moment required to flex the hand

Fig. 3. OpenSim [12] Simulation of the fiber length and moment while flexing the arm from a relaxed position to a full biceps curl for an average sized man.

After discussing the design considerations made, we detail the physical construction of the exosuit and the results yielded as various activities are performed by the user donning CRUX. Finally, we conclude with a brief summary of observations made throughout the paper as well as the direction of future investigations.

II. SYSTEM DESIGN

The primary focus of our work is to develop a lightweight, compliant design that is form-fitting to the human profile while maintaining structural integrity and strength. A lightweight and low profile suit is more portable, which could eventually promote muscular rehabilitation through ease of use [13]. Portability may increase the frequency of potential physical therapy sessions and exercises, which are essential in the rehabilitation efforts that combat many physical disabilities. Elasticity also provides comfort for users because it is less restrictive, unlike comparable rigid structures. Additionally, a user can theoretically perform a larger set of activities in a more flexible exosuit than its rigid counterpart. In this section, we discuss how these desirable attributes are achieved through the design of the exosuit and its interface with the user.

The human body is an inherently dynamic surface which, through muscular contraction, rapidly changes both its morphology and its rigidity. As a result, securing objects to the base layer of the exosuit, such as mechatronic parts and cables becomes non-trivial. To comply with these constraints, we used a design inspired by naturally occurring lines of non extension on the human body. Lines of non extension exist on the skin which neither stretch nor compress as a human moves. The position of such lines varies little from person to person [14], [15]. By placing housing and other fastened items along the skin's lines of non-extension, we sought to maximize the flexibility of the exosuit while providing necessary support and routing.

CRUX features a neoprene base substrate which is 2 mm thick on the torso and 1 mm thick on the arms. Neoprene provides a hyper-elastic medium to handle the large range of motion one would expect of upper extremities while providing enough stiffness to support anchored parts. This substrate also acts as a compression suit, promoting blood circulation while firmly fixing the suit in place on the body [16].

Actuation in CRUX is accomplished on the base layer and is cable-driven akin to the tendons in a human body. Similar to how tendons mechanically transfer power from the muscle to the skeleton, these cables transfer power from the motor to the exosuit. Bowden housing, composed of bicycle braking cable housing, routes spectra fishing line rated to 80 lbs (360 N) across contours of the body. The Bowden housing also reduces friction of the cables against the neoprene base layer. Upon CRUX's neoprene surface, the sections of Bowden housing are anchored with neoprene cement. As a result, bare cable passes slightly above the neoprene, allowing for flexibility at the joints of the user. The spooled cables of CRUX are distally punctuated with anchors directly attached to the neoprene. Each anchor point consists of a 2 cm wide D-ring that is fastened to the neoprene surface by way of sewing a neoprene strip over the base of the D-ring and to the neoprene surface. Neoprene cement is then applied to this strip to further increase the shear threshold of each anchor.

Seven cables are mapped onto the base layer above major muscles in the upper-extremity to directly apply augmentative forces (Figure II, Table I). We selected which muscles to support with exosuit cables according to those muscles' impact on overall arm dynamics and kinematics (i.e. size and strength of the muscle).

CRUX operates six micromotors on a modular plate attached to the dorsal side of the suit. During actuation, cables functioning as tendons are spun around spools attached to the spindles of these motors. Each motor corresponds to a single cable/tendon with the exception of the forearm rotation motor. In the case of pronation and supination of the forearm, both cables are antagonistically attached to the same motor such that the displacement of one is inversely

TABLE I

CABLES AND THE MOVEMENTS THEY INDUCE. REFERS TO FIG. II.

Targeted Muscle Group	**Movement Created**	**Cable**
Biceps	Flexion about elbow	Red
Triceps	Extension about elbow	Blue
Deltoids	Shoulder abduction	Green
Supinators	Supination of forearm	Orange
Pronators	Pronation of forearm	Purple

proportional to the displacement of the other. These motors operate independently of one another to create six degrees-of-freedom.

A main controller, powered by a separate lithium-ion battery, operates the motor driver module through a I2C bus. This type of interface give the suit the scalability necessary for potentially more motors in future designs. The main controller is a custom design circuit board that allows for closed loop control through the use of a built-in IMU. Using ultra-wide band (UWB) wireless connectivity, the controller can connect to the additional IMUs on the exosuit.

A. Control

CRUX can be controlled through either closed-loop control or human-in-the-loop control.

The pose data obtained by the IMU network of the exosuit can be used by the on-board microcontroller to influence an arbitrary control law (e.g. an isometric or an isotonic muscular movement). The microcontroller uses 32 KB of memory storage, enough for basic data types and structures.

The option for manual control of a particular singular cable or pair of cables can be accomplished by an attached two-axis analog joystick. Additionally, all motors can be simultaneously manually operated by an attached laptop with the appropriate control software installed on it.

B. Safety

The design of all human interfacing robots, including exosuits, requires inherent safety. The theoretical maximum torque of each motor is 125 oz in (0.883 Nm). Given a spool radius of 1.0 cm, the maximum force output along any particular cable is never more than 88.3 N. Users who operated CRUX were made aware of this level of strength and acknowledged that in the event of an emergency, they would be able to overpower the exosuit thus overriding any dangerous actuation. As a further failsafe, the battery powering every motor is easily detachable from the circuit as well as the exosuit itself in the event of overheating.

III. RESULTS AND DISCUSSION

We observed the performance of CRUX as we conducted a series of experiments to investigate our claims that the exosuit maintains high flexibility without sacrificing augmentation.

Cable Map of CRUX

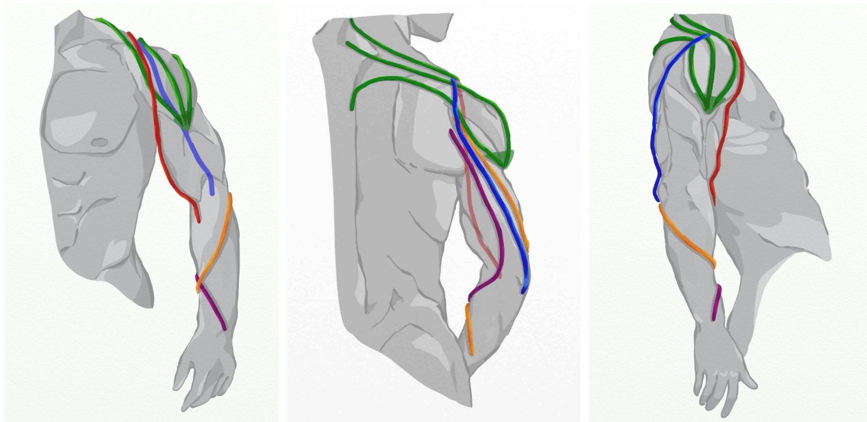


Fig. 4. The cable mapping of CRUX. Each cable directly focuses on a single movement outlined in Table I

CRUX Control Loop

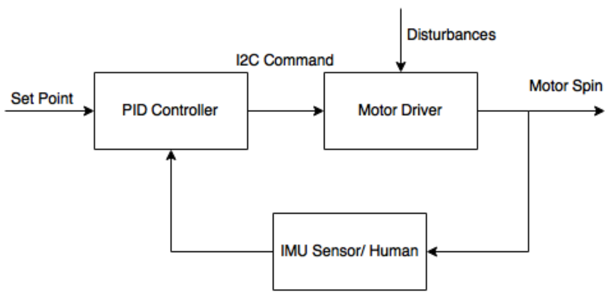


Fig. 5. The closed loop control loop for CRUX. The feedback provided can come from IMUs on the exosuit or directly from the user when manually controlled.

A. Case Study

Five participants performed a series of exercises, with and without the exosuit to determine the efficacy of the exosuit. Four of these participants served as a control group of unimpaired individuals against which the fifth participant, a stroke survivor, was compared.

Participants began by first demonstrating their range of motion when donning the exosuit. To measure the flexibility of CRUX, a motion capture system tracked users throughout the study to provide kinematic data. The range of motion of a user was measured while not donning the exosuit or any inhibitive clothing and then again while wearing the exosuit (Figure 7).

After the flexibility testing, the users were instructed to lift a dumbbell via biceps curl while seated and wearing a pulse oximeter to track their heart rate in real time. After resting for two minutes when the subject returned to their resting heart rate, the same procedure was repeated, but while donning CRUX. CRUX was operated by either the user manually with a joystick (Figure 1) or, when infeasible, by a second operator via laptop connection (Figure 6).

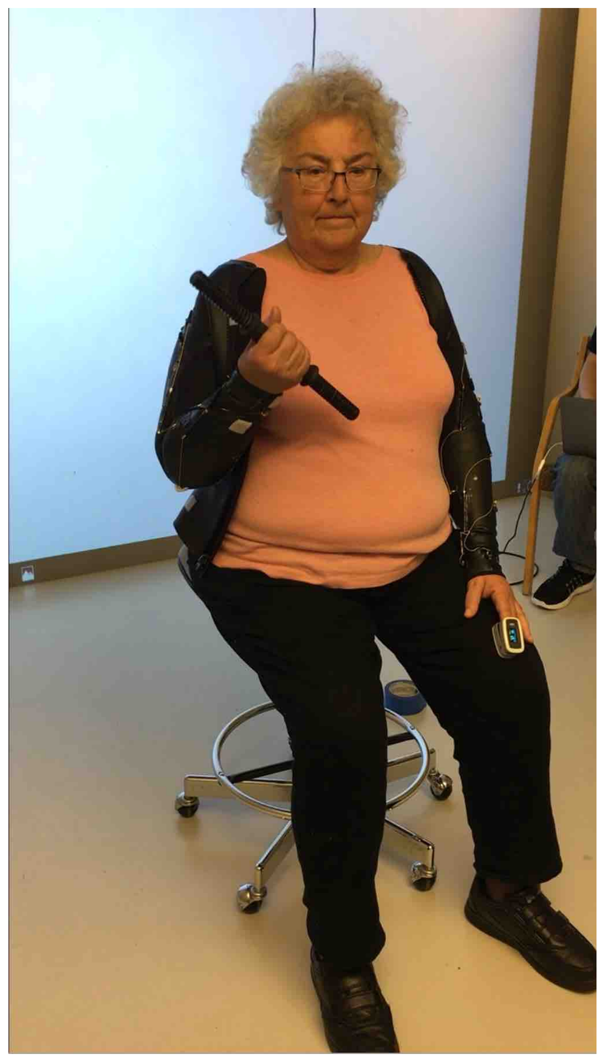


Fig. 6. One participant (a stroke survivor) using CRUX while an independent operator controls the exosuit harmoniously.

B. Results

The flexibility tests yielded no significant difference in the range of motion between donning the exosuit and not. Figure 7 illustrates the profile of one characteristic user as they moved their arm in space to the limit of their reach. This supports the notion that CRUX does not significantly obstruct movement upper-extremity. In Figure 7, straight lines can be observed, however these are not limitations of movement.

These straight lines are an artifact of the IR cameras losing track of the clusters in some positions. The method of mapping arm position falters when the infrared clusters can not be seen by enough cameras to extract the correct location, resulting in data being lost. However adjusting the clusters to be seen easier would conclude with a loss of range of motion due to the necessity of placement on the joints.

The dumbbell lifting exercise suggests that the activated exosuit decreases the effort required by the user to perform the function. Due to the relatively small sample size, we present the medians of the heart rate data. When unassisted, the median resting (starting) heart rate of participants prior to lifting the dumbbell is 61 bpm and the post-exercise heart rate is 81 bpm. When assisted, the median resting heart rate of participants prior to lifting the dumbbell is 61 bpm and the post-exercise heart rate is 77 bpm.

Figure 8 shows the heart rate of one subject (an unimpaired adult male) doing bicep curls with a $10lb$ $(44N)$ weight. Althought this subject's resting heart rate while wearing the exosuit was found to be 76 bpm (higher than average), they illustrate characteristic increase in heart rate throughout the exercise. The trial without actuation produces a highly variable and unsustained heart rate that increases to 95 BPM while the use of CRUX produces a slower and steadier increase in heart rate that never rises above 85 BPM. Even considering potential muscle fatigue due to the prior trial, the subject maintained a lower heart-rate when assisted by CRUX.

The stroke survivor who participated in study compared and contrasted with the other participants in some intriguing ways. First, despite not perfectly conforming to the exact dimensions of the exosuit, she was able to don CRUX nonetheless and complete each exercise in full. Additionally, when provided a dumbbell of appropriate mass (4 lbs or 1.8 kg) to test her muscular strength and endurance, she also experienced a lesser increase in heart rate when donning CRUX (61 bpm to 62 bpm) than when not (61 bpm to 67 bpm). This suggests that the exact conformity required by CRUX may be less than we had initially believed. To confirm this new hypothesis, more participants must be recruited and studied.

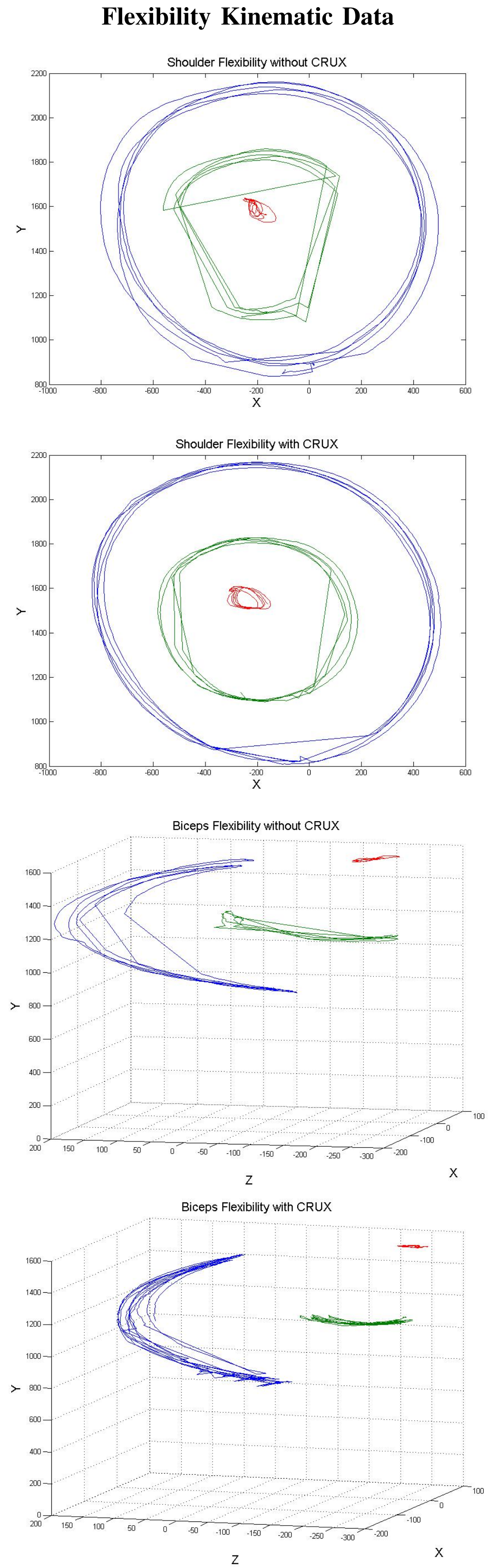


Fig. 7. The augmentative suit does not impede the range of motion. The figure shows the location of 3 markers (red for shoulder, green for elbow and blue for hand) with and without CRUX.

IV. CONCLUSIONS

Through our experiments, we have observed that CRUX provides a lightweight, compliant upper-extremity solution for meaningful and useful augmentation of human movements without sacrificing flexibility. These findings warrant future investigations to verify our results and further development of the exosuit itself to improve capability.

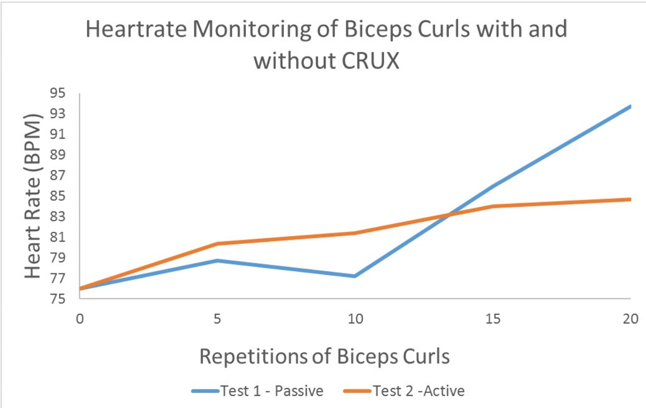


Fig. 8. Heart rate measured while doing 20 repetitions of biceps curls with CRUX (Orange) and without CRUX (Blue) using a 10lb (44N) dumbell

Prior exoskeletons and exosuits have illustrated augmentation through tendon-based cable actuation; CRUX builds upon these advancements by augmenting the upper-extremities of individuals through multi-DOF, compliant, structure. These particular attributes are valuable in situations where traditional rigid, heavy exoskeletons are too cumbersome or immobile for portable use.

The exosuits exhibited insignificant inhibition to the range of motion of users who properly fit the dimensions of the exosuit. Additionally, a pilot study on the effect of the powered exosuit during an exercise found that for the five participants, there was less of an increase in heart rate when using the exosuit to perform arm curls with a weighted dumbbell than when not donning the exosuit.

Further investigations can help to refine CRUX and develop future methods to better increase the metabolic impact CRUX has on its user. One important metric to judge future work upon, is the overall metabolic cost of the exosuit on a user. The true augmentation factor of an exosuit must be judged not only by its assistance to the user, but also its own overhead (i.e. its mechanical efficiency).

The development of proprioception in an exosuit can promote a more fluid human-robotic interaction. By combining real-time sensed information with predictive control, an exosuit theoretically can adapt itself to augment a user quickly, robustly and effectively. An important aspect of proprioceptive control, however, is user adoption. Although this hypothetical controller could potentially react more quickly and learn from prior examples and test data, this does not confirm that users will respond positively to the technology or even adopt the wearable robot at all. The determination of this adoption can be discovered and accounted for with further studies and iterations of the robot.

ACKNOWLEDGMENT

The authors would like to thank Vytas SunSpiral, Linda Luu, and Gersain Chevarria for their support in the early designs of the exosuit and Cabrillo College Stroke and Disability Learning Center for allowing us to recruit participants.

The authors would also like to thank Leonard Norton for providing advice on the physical therapy movements that were translated into exosuit supported movements. This material is partly based upon work supported by the National Science Foundation under Grant No. CNS-1229786. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation.

REFERENCES

[1] A. Iscen, A. Agogino, V. SunSpiral, and K. Tumer, “Learning to control complex tensegrity robots,” in *AAMAS*, 2013.

[2] S. Lessard, J. Bruce, E. Jung, V. SunSpiral, T. Mircea, and A. Agogino, “A Lightweight, Multi-axis Compliant Tensegrity Joint,” in *Proceedings of 2016 IEEE International Conference on Robotics and Automation, (ICRA2016), May 2016, Stockholm, Sweden*, 2016.

[3] L. B. Baltaxe-Admony, A. Robbins, E. Jung, S. Lessard, M. Teodorescu, V. SunSpiral, and A. Agogino, “Simulating the Human Shoulder through Active Tensegrity Structures,” in *Proceedings of ASME 2016 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference (IDETC/CIE), August 21-August 24, 2016, Charlotte, NC, USA*.

[4] J. Friesen, A. Pogue, T. Bewley, M. de Oliveira, R. Skelton, and V. Sunspiral, “Ductt: a tensegrity robot for exploring duct systems,” in *Robotics and Automation (ICRA), 2014 IEEE International Conference on*. IEEE, 2014, pp. 4222–4228.

[5] Y. Mao and S. K. Agrawal, “Design of a cable-driven arm exoskeleton (carex) for neural rehabilitation,” *IEEE Transactions on Robotics*, vol. 28, no. 4, pp. 922–931, 2012.

[6] X. Jin and S. K. Agrawal, “Exploring laparoscopic surgery training with cable-driven arm exoskeleton (carex-m),” in *2015 IEEE International Conference on Rehabilitation Robotics (ICORR)*. IEEE, 2015, pp. 490–495.

[7] R. D. Kornbluh, A. S. Kernbaum, T. Low, K. G. Witherspoon, B. K. McCoy, A. A. E. Ziemba, P. M. Birkmeyer, and R. M. Mahoney, “Exosuit system,” Feb. 23 2016, uS Patent 9,266,233.

[8] A. T. Asbeck, R. J. Dyer, A. F. Larusson, and C. J. Walsh, “Biologically-inspired soft exosuit,” in *Rehabilitation robotics (ICORR), 2013 IEEE international conference on*. IEEE, 2013, pp. 1–8.

[9] N. Tsagarakis, D. Caldwell, and G. Medrano-Cerda, “A 7 dof pneumatic muscle actuator (pma) powered exoskeleton,” in *Robot and Human Interaction, 1999. RO-MAN’99. 8th IEEE International Workshop on*. IEEE, 1999, pp. 327–333.

[10] S. Sovero, N. Talele, C. Smith, N. Cox, T. Swift, and K. Byl, “Initial data and theory for a high specific-power ankle exoskeleton device.”

[11] I. Galiana, F. L. Hammond, R. D. Howe, and M. B. Popovic, “Wearable soft robotic device for post-stroke shoulder rehabilitation: Identifying misalignments,” in *Intelligent Robots and Systems (IROS), 2012 IEEE/RSJ International Conference on*. IEEE, 2012, pp. 317–322.

[12] S. L. Delp, F. C. Anderson, A. S. Arnold, P. Loan, A. Habib, C. T. John, E. Guendelman, and D. G. Thelen, “Opensim: open-source software to create and analyze dynamic simulations of movement,” *IEEE transactions on biomedical engineering*, vol. 54, no. 11, pp. 1940–1950, 2007.

[13] M. S. De Carlo and K. E. Sell, “The effects of the number and frequency of physical therapy treatments on selected outcomes of treatment in patients with anterior cruciate ligament reconstruction,” *Journal of Orthopaedic & Sports Physical Therapy*, vol. 26, no. 6, pp. 332–339, 1997.

[14] A. S. Iberall, “The use of lines of nonextension to improve mobility in full-pressure suits,” DTIC Document, Tech. Rep., 1964.

[15] A. M. Wessendorf and D. J. Newman, “Dynamic understanding of human-skin movement and strain-field analysis,” *IEEE Transactions on Biomedical Engineering*, vol. 59, no. 12, pp. 3432–3438, 2012.

[16] D.-P. Born, B. Sperlich, and H.-C. Holmberg, “Bringing light into the dark: effects of compression clothing on performance and recovery,” *Int J Sports Physiol Perform*, vol. 8, no. 1, pp. 4–18, 2013.