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

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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 underlying complexity of the 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 multi-joint design for portable augmentation. We also illustrate how CRUX maintains the full range of motion of the upper-extremities for its users while providing multi-DoF strength amplification 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. Soft Robotics and Tensegrity

The field of soft robotics features machines constructed out of "soft" materials, which are compliant and could conform to the environment during operation, which could function more similarly to the human body than rigid robots. 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]. Stemming from this property, there are many similarities 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.

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.

Fig. 1. A user playing a game in virtual reality using CRUX: a soft, lightweight ($1.3kg$), robotic exosuit for upper-extremity augmentation

Additional analysis regarding the human body can be achieved through biomimetic simulators. For example, the Arm26 OpenSim [5] model can be used to estimate the kinematics and dynamics of an average size man flexing the right arm from relaxed position to full biceps curl. Figure 2 shows the simulation at 3 different time steps. Figure 3(a) shows the change in fiber length for different muscle groups and 3(b) the moment applied around the elbow joint. This model exemplifies the antagonistic relationship between different muscle groups, a factor critical in the design of human-inspired robots. While the length of the

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biceps (agonist muscle) fiber decreases from contraction, 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.

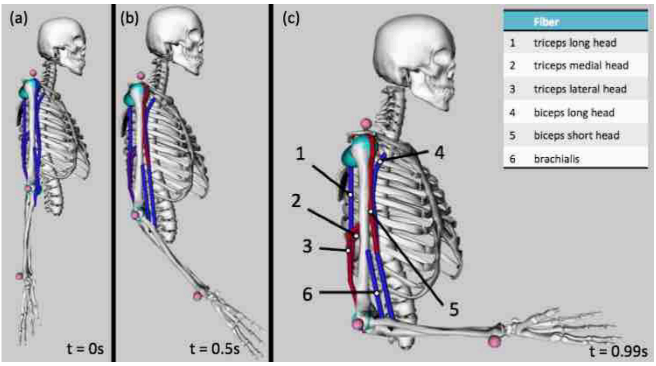
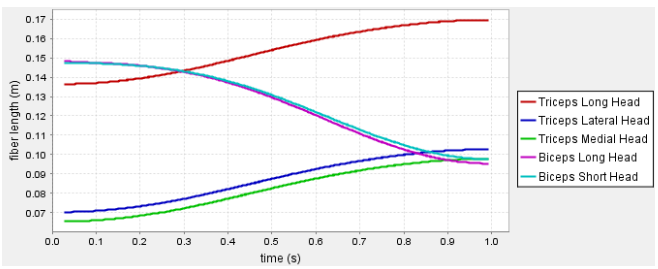
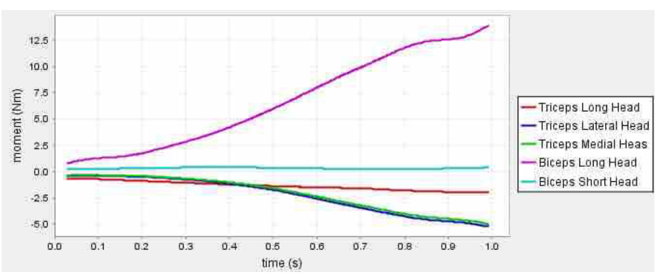


Fig. 2. OpenSim [5] simulation a flexing the arm from relaxed position to biceps curl for an average sized man.



(a) Fiber length



(b) Moment required to flex the hand

Fig. 3. OpenSim [5] 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.

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 [6], [7].

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 [8], [9]. The pneumatically driven exosuits from Tsagarakis et al. and commercial groups such as Roam of OtherLabs also promote compliant augmentation through soft structures [10], [11].

Augmentative exosuits for the upper-extremities have similar goals. One such exo-brace by Galiana 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 [12]. 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. An exosuit by Xiloyannis et al. further develops this concept and applies textile-based augmentation to the elbow and wrist. These advancements are critical steps towards full-arm augmentation. To achieve this eventual goal, every joint in the arm (and every degree of freedom naturally capable) must be accounted for in the wearable robot.

Our proposed research demonstrates a flexible multi-degree of freedom, multi-joint augmentation exosuit for the upper extremity called Compliant Robotic Upper-extremity eXosuit (CRUX). This exosuit enables augmentation according to four pairs of motion primitives: wrist pronation and supination, elbow flexion and extension, lateral shoulder raise and lower, and forward shoulder raise and lower.

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.

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 wearing 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 main goal of the current research is to develop a low profile, lightweight, portable, compliant form-fitting exosuit, which is strong enough to augment user motion with minimal discomfort. We envision that a future iteration of the current design could be worn under regular clothing without altering user’s appearance [13].

Portability may increase the frequency of physical therapy sessions and exercises, which are essential in the rehabilitation efforts that combat many physical disabilities. Additionally, a user can 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 system, which rapidly changes both its morphology and its rigidity through muscular contraction. The electronic and mechanical systems attached to the exosuit should be able to augment user's abilities, without restraining body motion. To achieve this, the actuation cables were laid using a design inspired by naturally occurring lines of non-extension on the human body. These preferential routes exist on the skin which neither stretch nor compress as the human moves and varies little from person to person [14], [15]. Consequently, this approach maximizes the flexibility of the exosuit while providing optimal support and routing for the actuation.

The proposed exosuit features a 2 mm thick neoprene base substrate on the torso and 1 mm thick on the arms. Neoprene provides an 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].

The actuation of the exosuit is achieved using a cable-driven system akin to the tendons in a human body, which mechanically transfer power from the muscle to the skeleton. Seven cables were mapped onto the base layer above major muscles in the upper-extremity to directly apply augmentative forces (Figure 4, Table I). The augmented muscles were chosen based on their impact to the overall arm dynamics and kinematics (see the simulation in Figure 2 and 3).

The cable driven system consist of spectra fishing line rated to 80 lbs (360 N) routed along specific contours of the body inside segments of Bowden housing to reduce cable friction against the neoprene base layer without inhibiting arm flexibility. The actuation lines are anchored on the suit using a system of specially designed attachments, which distribute the surface shear over a larger area. Neoprene cement is then applied to this strip to further increase the shear threshold of each anchor.

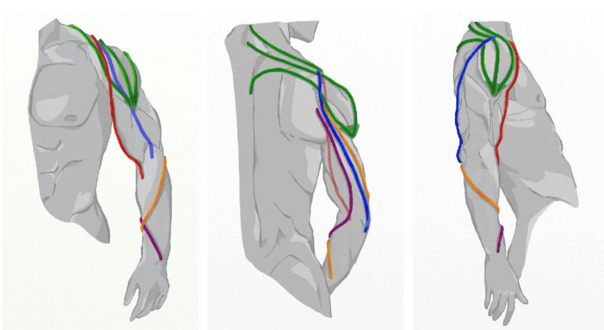


Fig. 4. The cable mapping of CRUX. Each cable directly focuses on a single movement outlined in Table I

We conducted an experiment to quantify the magnitude of the deformation of specific lines on the arm and locate the optimal lines of non extension to be used. Figure 5 (left) shows the location of 65 infrared tracking nodes placed on a human arm. During the experiment, a user replicated the set of exercised performed during a physical therapy session, while the location of the tracking nodes was monitored by a motion capture system consisting of 8 high precision, low-latency, ultra-wide field of view cameras (OptiTrak Prime 13W). The standard deviation of the distances between points during the experiment was normalized against the distance between the same points while the arm is at rest (Figure 5 (right)). The normalized matrix of distances was predicted as:

TABLE I

CABLES AND THE MOVEMENTS THEY INDUCE. REFERS TO FIG. 4.

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

$$N_{k_{ab}} = \frac{||P_{k_a} - P_{k_b}||_2}{|P_a - P_b|}$$

Where P_{k_a} and P_{k_b} are the position vectors of nodes a and b and N_{ab_k} is the normalized matrix of distances at time step k. The standard deviation of the set of data is computed as:

$$S_{ab} = \sqrt{\frac{1}{n}\sum_{k=1}^{n}(N_{k_{ab}} - \overline{N}_{k_{ab}})^2}$$

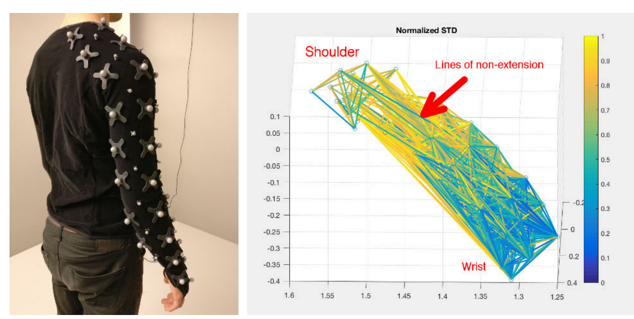


Fig. 5. Determining the lines of non extension. Left - the experimental setup. Right - Normalized standard deviation of the distances between points during the experiment. Blue lines are optimal

Each arm of the exosuit is actuated by six micromotors installed on a modular plate attached to the dorsal side of the suit. During operation, cables/tendons are spun around spools actuated by 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 proportional to the displacement of the other. All of the motors operate independently to create a six degrees-of-freedom system.

The exosuit can be controlled either as human-in-the-loop control (using a two-axis analog joystick for testing) or closed-loop. The main controller is a custom-designed circuit board that uses 32 KB of memory storage, and operates the motor driver module through a I2C bus. The system includes a set of built-in IMUs (2 on each arm) which use an ultra-wide band (UWB) wireless connectivity. The IMU network is used for the closed loop control system to implement semi-autonomous control (interruptible by user action). The motors are powered by a three-cell 3500 mAh lithium polymer battery which provides $11.1 - 12.6V$ and up to $50A$.

This type of interface gives the suit the scalability necessary for for future improvements. Figure 6 shows CRUX on a mannequin with its mechatronic components labeled. Figure 7 illustrates the closed loop control strategy implemented to demonstrate our designs as a proof-of-concept.

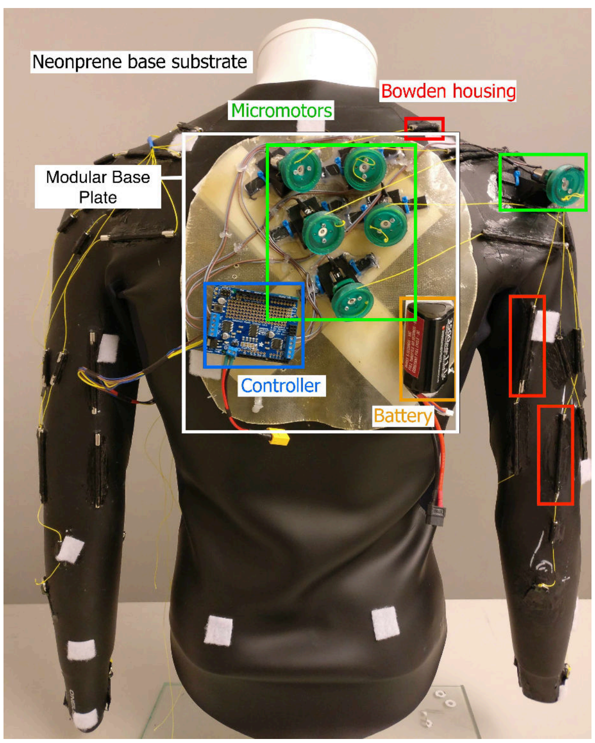


Fig. 6. CRUX: System Components

A. 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.

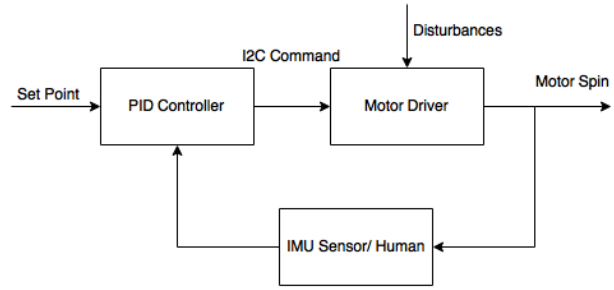


Fig. 7. The closed loop control loop for CRUX. The feedback provided can come from IMUs on the exosuit or directly from the user when manually controlled.

III. RESULTS AND DISCUSSION

The goal of the preliminary experiments presented here was to establish if indeed, the proposed CRUX exosuit could augment user's activities, without inhibiting motion.

A. User Study

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

To test the flexibility of CRUX, we first documented each participant's natural range of motion using the OptiTrack motion capture system. Each participant was asked to remove any inhibitive clothing and do a series of stretches first without and then donning CRUX in a passive state. These stretches included large arm circles, biceps curls, and supination and pronation of the arm.

After flexibility testing, the users were seated and instructed to lift a dumbbell via elbow flexion (biceps curl) 20 times. The participant's heart rate was tracked in real time with a pulse oximeter. After returning to their resting heart rate, the exercise was repeated while wearing the proposed exosuit. During this test, CRUX was operated by the user manually with a joystick (Figure 1), which allowed the user to assist the movement of their biceps. One participant had limited mobility and was not able to use the joystick. In this situation, CRUX was controlled by a second operator via laptop connection.

B. Results

The flexibility test revealed (Figure 8) that there is no significant change in the user's natural range of motion while wearing CRUX. The figure illustrates the profile of one characteristic user as they move their arm through space to the outermost limit of their reach with without and with the augmentative exosuit. This supports the notion that the proposed system does not significantly obstruct upper-extremity movements. In Figure 8, straight lines can be observed, however these are not limitations of movement, but an artifact of the motion tracking system.

The dumbbell lifting exercise suggests that the activated exosuit decreases the effort required by the user to perform

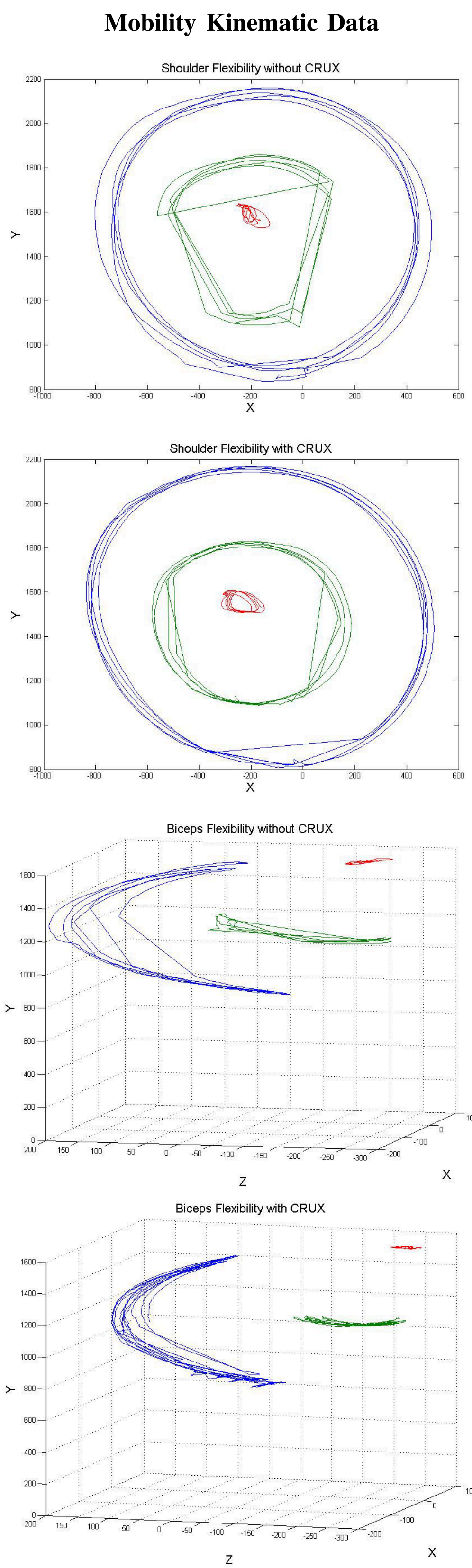


Fig. 8. The range of motion of one participant in a 3D space without and with the augmentative exosuit. Red marks shoulder movement, green elbow, and blue hand. Shoulder mobility was demonstrated by large arm circles. Elbow mobility was demonstrated by biceps curls.

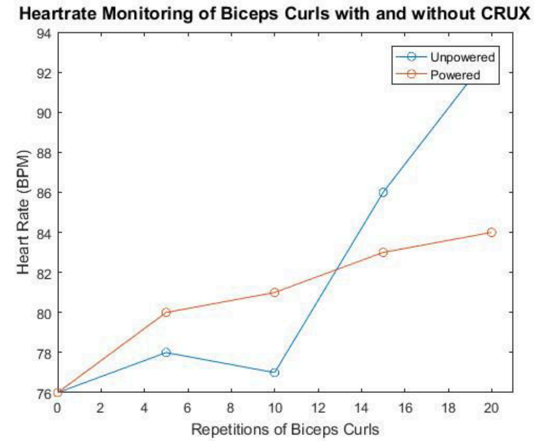


Fig. 9. Heart rate of one characteristic user measured while doing 20 repetitions of biceps curls with CRUX (Orange) and without CRUX (Blue) using a 10lb (44N) dumbbell

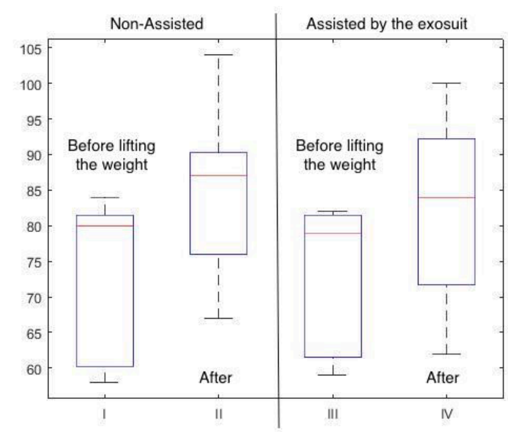


Fig. 10. Measured heart rate of five participants : (I) Before lifting the weight without exosuit (II) After lifting the weight without exosuit (III) Before lifting the weight with exosuit (IV) After lifting the weight with exosuit

the function (see Figure 10). When unassisted, the median resting (starting) heart rate of participants prior to lifting the dumbbell is 80 bpm and the post-exercise heart rate is 87 bpm. When assisted, the median resting heart rate of participants prior to lifting the dumbbell is 79 bpm and the post-exercise heart rate is 84 bpm.

Figure 9 shows the heart rate of one subject (an unimpaired adult male) doing bicep curls with a $10lb$ $(44N)$ weight. Although 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.

For a case study, we observed a stroke survivor use CRUX while lifting dumbbells. This participant was provided a dumbbell of appropriate mass (4 lbs, equivalent to 1.8 kg) to test her muscular strength and endurance. The stroke survivor experienced less of an increase in heart rate when using CRUX (61 bpm to 62 bpm) than when not (61 bpm to 67 bpm). This is particularly impressive considering the exosuit did not perfectly fit the participant. We initially believed an imperfect fit of the exosuit would yield ineffective actuation, but the results disagreed with that hypothesis. This suggests that the exact level of conformity required by CRUX to augment the user may be lower than we had initially believed.

Figure 10 shows the heart rate data from the five participants before and after lifting weight with and without donning the exosuit. As this figure indicates, across all participants, the exosuit causes less increase in heart rates after weightlifting. The difference is statistically significant, with a median of 7 bpm without the exosuit and 5 bpm with the exosuit.

IV. CONCLUSIONS

Through our experiments, we have observed that CRUX provides a lightweight, compliant multi-joint 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. 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 proposed design exhibited insignificant inhibition to the range of motion of users who properly fit the dimensions of the exosuit. Additionally, a case 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 the 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.

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