Abstract—Stroke is the leading cause of adult disability. Many robots have been developed to administer movement therapies or provide physical assistance to stroke survivors suffering from movement deficits. One effective approach has been to support the weight of the arm, offloading shoulder abductor muscles that have become coupled to elbow muscles. However, patients have limited access to such robots due to the robots’ complexity, cost, and bulk. To counter this problem, we developed a lightweight (350 g), inexpensive external actuator, which we call an exomuscle. We constructed a prototype exomuscle by reinforcing a plastic bladder with a fabric bag that is sewn to supporting straps. The bladder can then be inflated with pressurized air to provide expansive forces between the user’s torso and arm, supporting shoulder abduction. A seam acting as a hinge joint connects the exomuscle to the torso. We demonstrate that our exomuscle reduces muscular effort by 74% in isometric tasks and 72% in dynamic reaching tasks while minimally affecting the range of motion of the shoulder and elbow (average 4% reduction) on three users ranging from 165 to 188 cm tall. Future studies will evaluate the exomuscle with users who have post-stroke motor impairments.

I. INTRODUCTION

Stroke results from significantly reduced blood supply to part of the brain and is one of the leading causes of long-term adult disability [1]. Stroke survivors can suffer from a large range of negative effects such as pain, spasticity (continuous contraction of some muscles), muscle weakness, hemineglect (unawareness of half of space), and cognitive deficits. Some researchers believe that the main cause of post-stroke motor impairment is abnormal muscle co-contractions [2]. These abnormal muscle co-contractions were first observed as the coupling of shoulder abductor with elbow flexor muscles and shoulder adductor with elbow extensor muscles [3]. Since then, post-stroke abnormal muscle co-contraction patterns have been observed for a range of upper extremity tasks [4], as well as for walking [5]. While there is a highly nonlinear relationship between the electromyographical (EMG) signals on which these analyses are based and the resultant joint torques, abnormal joint torque couplings have been found that match the EMG-based results [6]. These researchers have also demonstrated substantial improvements in motor function, achieved by supporting the weight of the hemiparetic arm with an air bearing, which unloads the shoulder abductor muscles [7].

Many researchers are developing robots to work with humans with neuromotor impairments for assistance or re-habilitation. A large number of these robots are designed to help users repeatedly perform a task [8], [9], but this approach might not be optimal for stroke rehabilitation [10], [11]. Building on the results from [7], Ellis et al. [12] designed and built an impairment-specific rehabilitation robot, ACT3D, to provide shoulder abduction support. They then administered a therapy in which shoulder abduction support was gradually reduced over a period of eight weeks and found several motor improvements [12], [13]. However, the level of motor recovery is tied to the intensity of therapy, and most rehabilitation robots are expensive, unwieldy devices confined to the lab or clinic where patients have limited access to them.

Many of the robots currently being developed for rehabilitation are exoskeletal robots. Typical exoskeletal robots are constructed from rigid linkages acting in parallel with the user’s skeleton. These linkages are then attached at various points on the body by cuffs or straps to transmit forces and torques. Motors or hydraulic actuators then actuate these linkages. By including linkages acting in parallel with the user’s skeleton, an exoskeleton transmits many of the forces that would otherwise need to be transmitted through the user’s skeleton. Such exoskeletal robots have already been developed for stroke rehabilitation [8], [12], [13]. These robots show promise in taking state-of-the-art rehabilitation out of the clinic. However, there are many difficulties associated with the design and operation of traditional exoskeletal robots, including cost, aligning operator and robot joint axes [14], safely handling the mass added by the exoskeleton, and ensuring stable interactions with human users [15], [16]. Further, exoskeletal robots might be excessive for tasks that do not require load-bearing beyond the capability of the human skeleton.

To address the problems associated with traditional exoskeletal robots, several groups have recently built soft exosuits that forgo rigid linkages and directly apply forces and torques to the user’s skeleton instead. Eliminating rigid linkages allows exosuits to be constructed of primarily compliant materials that require less precise design and machining, are lightweight, and are generally inexpensive. However, without rigid linkages, applying forces and torques to the human body can be difficult. Some designs use inelastic cables intelligently placed on the body and anchor points to transmit loads to specific body parts [17], [18]. While these designs have proven effective, they increase the compressive...
II. DEVICE DESIGN AND CONSTRUCTION

We designed and built a prototype exomuscle from fabric reinforced inflatable bladders to provide low-cost shoulder abduction support that minimally interferes with range of motion for stroke rehabilitation and assistance. The exomuscle consists of twin plastic bladders that have been reinforced by fabric bags sewn to the desired final shape of the device. A flow chart of the construction process is shown in Fig. 2. The final exomuscle is roughly triangular when viewed from the user’s front or back, and has a Y-shape when viewed from the side (Fig. 2, top left). The V-shape at the top of the Y creates a stable support for the arm that prevents the arm from falling off the support during movements. The completed exomuscle was then sewn onto a shoulder mount that holds the exomuscle next to the torso and under the arm of the user with a single seam that acts as a hinge joint. The exomuscle is attached to the user’s waist by a polypropylene waistbelt. Elastic straps help to hold the arm in place on top of the exomuscle. Compressed air is pumped into the exomuscle to provide expansive forces between the attachment points on the human body: the seam along the torso and the underside of the arm. We used a portable compressor to inflate the exomuscle. While 27.5 kPa was sufficient pressure to provide significant support to our users, we inflated the exomuscle to 55 kPa without failure.

III. EXPERIMENTAL METHODS

A. Device characterization

To control the exomuscle, we need to know the relationship between the input air pressure and the resulting shoulder abduction angle. Thus, we measured the relationship between air pressure in the bladder and shoulder abduction angle by inflating the exomuscle to air pressures of 0, 6.9, 13.8, 20.7, and 27.5 kPa while recording the shoulder abduction angles at each pressure with a visual tracking system for each of three users.

To ensure comfortable and safe interactions, we need to understand the interaction forces between the exomuscle and the arm. We measured the relationship between shoulder abduction angle and the interaction forces between the exomuscle and the upper arm by attaching the exomuscle to a one-degree-of-freedom test apparatus. The test apparatus consisted of two linkages connected by a hinge joint. The exomuscle was connected to the two linkages of the test apparatus so that one linkage acted as a torso and the other acted as an arm. The hinge joint acted as a simple shoulder. The exomuscle was inflated to 6.9, 13.8, 20.7, or 27.5 kPa and then compressed by rotating the two linkages of the test apparatus towards each other (similar to shoulder adduction). We recorded the deflection angle with a visual tracking system and the interaction forces between the exomuscle and the test apparatus linkage representing the arm with a three-axis force transducer (ATI Mini45) connected between the two.

B. Range of motion

Traditional exoskeletons limit the user’s range of motion, which limits their utility. To determine how our device affects upper extremity range of motion, we used a goniometer to measure the extrema of shoulder internal/external rotation, shoulder horizontal abduction/adduction, and elbow flexion/extension for three users, under two conditions: (1) with the exomuscle inflated to approximately 27.5 kPa, and (2) without any exomuscle.

Fig. 1. Exomuscle schematic and prototype images. A. Schematic of our exomuscle, which attaches under the arm and against the torso and is held in place with assorted straps. A single seam running down the torso acts as a hinge to allow free shoulder horizontal abduction. The exomuscle is inflated by a compressed air source. Inflating the exomuscle causes expansive forces between the seam against the torso and the arm. B. A user wears the exomuscle in its uninflated state. C. A user wears an inflated exomuscle.
**Fig. 2. Exomuscle construction.** A. Photograph of a completed exomuscle. Inset: V-shaped part that supports the arm. B. Diagram of a finished exomuscle. C. The construction process of the fabric bag used to reinforce plastic bladders to create the exomuscle. First, four pieces of canvas fabric are cut to the shape shown in C.1. Two of these pieces are sewn together with the seam shown in C.2. A third piece of canvas is placed on top of the two previously sewn together and the top two canvas pieces are sewn together with the seam shown in C.3. That assembly is then flipped over and the fourth piece of canvas added and sewn to the piece directly under it as shown in C.4. This series of steps creates a stable V-shaped support for the arm. Finally, all four pieces of canvas are sewn together with the seam shown in C.5. D. The construction process for twin bladders that line the exomuscle. The bladders are created from plastic bags (D.1.). Plastic tubes are inserted into one end of the plastic bags. The bags are then heat sealed around the plastic tubes to ensure that air cannot escape as shown in D.2. The two bladders are then inserted into the fabric bag previously sewn to create a finished exomuscle. The exomuscle is then sewn to various straps to attach it to the user (B). Note that the single seam attaching the exomuscle to the torso acts as a hinge joint. The price of each component is listed in United States Dollars. These components total $16.34 USD.

**C. Muscular Effort**

**Isometric task:** To determine whether our exomuscle can reduce shoulder abductor muscle effort in an isometric task, we recorded neural activity in both the anterior and medial components of the deltoid muscle in three users during a series of isometric arm holds using electromyography (EMG). Each isometric hold was performed in one of three postures (Fig. 3, top left): (1) shoulder horizontally abducted to 90° (straight in front of the torso), (2) shoulder horizontally abducted to 45°, or (3) shoulder horizontally abducted to 0° (straight out to the side) with the elbow fully extended and the arm raised to shoulder height. EMG data was collected for ten seconds at 25 Hz using a Delsys Bagnoli 2 EMG system read by a Tektronix oscilloscope for each of these three postures with and without exomuscle support.

**Dynamic task:** To determine whether our exomuscle can reduce shoulder abductor muscle effort in a dynamic task, we again recorded EMG data from the anterior and medial components of the deltoid muscle in three users during a series of out-and-back reaches. Each reach began in the same posture: arm raised to shoulder height and elbow maximally flexed so that the hand was in front of the shoulder. Users then reached to one of three target points (Fig. 3, top right): (1) shoulder horizontally abducted to 90° (straight in front of the torso), (2) shoulder horizontally abducted to 45°, or (3) shoulder horizontally abducted to 0° (straight out to the side) with the elbow fully extended and the arm raised to shoulder height. After reaching a target posture, users...
Fig. 3. Electromyographical (EMG) data recorded during isometric (left column) and dynamic (right column) tasks. EMG data was recorded from both the anterior and medial deltoid while each task was performed in different conditions: (1) unassisted, (2) with exomuscle assistance, and (3) for the reaches with assistance provided by an air bearing. In most cases, exomuscle assistance significantly reduced muscular effort. On average, the exomuscle does not achieve the performance of the air bearing, but in some cases, such as user 3’s medial deltoid for all reaches, the exomuscle outperforms the air bearing.

returned their arm to the initial posture. EMG data was recorded throughout the reach, and kinematics were recorded by a visual tracking system. Users performed each reach in three support conditions: (1) unaided, (2) shoulder abduction supported by our exomuscle, or (3) arm weight supported by a custom air bearing. The air bearing allowed users to rest their arms on a table, but minimized friction forces in the plane of the tabletop. The air bearing support was included here to see whether the exomuscle could approach the performance of other established upper extremity support mechanisms in a dynamic task. The air bearing support was not included in the isometric task because there should be no neural activity in the deltoid muscles when the arm is fully supported in an isometric task. With our first user, we verified that the variance of resting noise was less than 0.22% of the signal variance from the unsupported case.

D. Users

We recruited three volunteer users for our air pressure versus abduction angle, range of motion, and muscle effort
Shoulder abduction angle, $\theta$ (deg)

-90  -70  -50  -30  -10

User 1  User 2  User 3  Mean

$\theta = 1.9p + 15.6$

Fig. 4. Abduction angle verses air pressure. Shoulder abduction angle increases nearly linearly with pressure for three different users (gray dashed lines). The black dashed line and error bars show the mean and standard deviations of the experimental data from each of the three users.

Studies. These users consisted of two right-handed males (height 171 and 188 cm) and a left-handed female (height 165 cm). All users wore the same exomuscle supporting the left arm with only the supporting straps adjusted for each individual.

IV. Results

We designed and constructed a prototype exomuscle that assists users in shoulder abduction. The prototype is inexpensive ($16.34 USD), lightweight (350 g), and made from entirely soft materials. While the prototype was made to the specifications of a 173 cm tall individual, we demonstrated its effective use on users ranging from 165 to 188 cm tall.

A. Device characterization

The exomuscle exhibits a linearly increasing relationship between air pressure and shoulder abduction angle (Fig. 4). This linear relationship is promising for future development of a feedback control system for arm positioning.

Interaction forces increase as shoulder abduction angle decreases and as air pressure increases (Fig. 5). In this way, the exomuscle behaves as a nonlinear spring whose resting position is maximal shoulder abduction and whose stiffness is tunable by modulating air pressure.

B. Range of motion

We compared the user range of motion with the exomuscle inflated to approximately 27.5 kPa and without the exomuscle. We found that shoulder internal/external rotation increased by 8%, shoulder horizontal abduction decreased by 13%, and elbow flexion/extension decreased by 8% (Fig. 6).

C. Muscular effort

**Isometric task:** To determine whether the forces applied by our exomuscle reduced users’ muscular effort, we recorded neuronal activity in select shoulder abductor muscles during a series of isometric holds and out-and-back reaches. We compared the variance of the electromyographical (EMG) signals when users were wearing the exomuscle inflated to approximately 27.5 kPa to that from unsupported trials (combined isometric and out-and-back reaches). Our results show that, on average, anterior and medial deltoid muscle activity decreased 73% (74% for isometric tasks, 72% for out-and-back reaches). In some cases, such as User 2’s anterior deltoid during a 0 degree hold (Fig. 3), muscle activity increased with exomuscle support. However, this phenomenon was usually observed when the muscle in question was not active in the unsupported case.

**Dynamic task:** We compare users’ muscular effort when...
using our device to that of another device designed to provide similar support in dynamic tasks. On average, using our exomuscle reduced the variance of recorded EMG signals by 72% from the unsupported case while the air bearing reduced the variance by 86% from the unsupported case.

V. DISCUSSION

The exomuscle is a one-size-fits-many device that has little impact on healthy users’ range of motion. While most exoskeletons require many adjustments for each new user due to the need to align joint axes, the exomuscle was effective on users ranging in height from 165 to 188 cm with minimal adjustments. The exomuscle greatly reduced muscular effort in both isometric and dynamic tasks (74% and 72% reduction of EMG variance from unassisted condition, respectively). In dynamic tasks, the exomuscle performed nearly as well as an air bearing (72% and 86% reduction from unassisted condition, respectively). We also demonstrated a linear relationship between air pressure in the exomuscle and shoulder abduction angle as well as a nonlinear spring behavior that can be used for position or impedance feedback control in future work.

We have demonstrated promising performance of our device with healthy users; future work aims to achieve improved performance and rehabilitative outcomes in motor impaired populations. Prior work shows that individuals with chronic post stroke motor impairment frequently have abnormal co-activations of the medial and anterior components of the deltoid muscle with other muscles [3], [23]. These studies also indicate that when shoulder abduction (which is largely performed by the deltoid) was supported by a robot, motor performance markedly increased [7]. Therapies in which robots gradually decrease the amount of support they provide have also yielded improved motor performance even without further robotic support [13]. Combining the reductions in muscular effort that we observed in the deltoid muscles with the largely preserved range of motion of other upper extremity degrees of freedom suggests that future studies involving users with chronic post-stroke motor impairments will yield similar results to those found in [7] and [13]. The low cost and high portability of our exomuscle might give patients the opportunity to have their own exomuscle at home that they can use daily to get much higher volumes of therapy. Therefore we might even see better results than traditional rehabilitation studies such as [13].

Several attempts have been made to make soft wearable robots. Many of them are gait-assist devices worn on the lower extremities [17], [18], but a few have also been developed for upper extremities [21], [22]. Like our device, Natividad and Yeow’s device [21] provides shoulder abduction assistance. However, their device behaves like a cantilever beam when inflated. While this device might yield some benefits to stroke patients, such as preventing stiffness in the shoulder, its usefulness for assisting patients to perform activities of daily living is limited. Because the exomuscle leaves remaining degrees of freedom unhindered, users are able to perform a wide range of tasks.

Future iterations of our exomuscle will focus on hardware improvements and controller development. Donning and doffing the prototype described here requires the attachment of several sets of straps. A complicated attachment procedure might prevent people with motor impairments from using our exomuscle, regardless of how effective it proves to be. We plan to streamline the attachment procedure by reducing the number of straps or incorporating the exomuscle into a shirt. Depending on the initial state of the device, we occasionally observe that the exomuscle buckles and provides less support or pushes the arm in an undesired direction. This problem can usually be corrected by increasing the air pressure. However, we prefer to operate the exomuscle at lower pressures to minimize required energy inputs. We believe that a wider exomuscle will be less likely to buckle, but at the expense of a larger profile and a larger amount of air required for operation. We also want exomuscle operation to be as intuitive as possible. Possible approaches include connecting the tube that inflates the exomuscle to another closed reservoir that can be operated by another limb or using electromyography-based controllers [24].

A key criticism of pneumatic devices is that they are reliant on a supply of compressed air or other fluid. While we used a grounded air supply for most of our experiments, we have also used a battery powered portable compressor to inflate the exomuscle. While noisy, the portable compressor inflates the exomuscle beyond the maximum air pressure used in testing within three seconds. Compressed gas reservoirs, such as those used to power paintball guns or quickly inflate bicycle tires, can also be used to repeatedly inflate the exomuscle due to the low air pressures required. While these devices have limited capacity, they are compact, lightweight, quiet, and many are refillable. The exomuscle can also be constructed as a closed system, in which air can pass from another reservoir into the exomuscle. The external reservoir could be actuated by another of the user’s limbs.

Design principles similar to those employed for the exomuscle could be used to develop a modular exosuit. While some exosuits that operate across multiple joints have already been developed [17], [18], these designs rely on multi-joint connections. The exomuscle, on the other hand, operates on a single degree of freedom without impinging on other degrees of freedom. Much like the human muscular system, which is made up of muscles specialized for their function, additional exomuscles could be developed with properties to fulfill specialized roles in a larger exomuscle “suit”.

The exomuscle increased shoulder internal/external rotation range of motion. While this increase might be an artifact of low user numbers, many researchers have demonstrated that certain muscles consistently act together even in healthy users [25]. As a result, the unloading of certain muscles in healthy users can result in an increase in range of motion [7].

While we designed our exomuscle for the needs of post-stroke motor impaired individuals, other populations might also benefit from this device. Several professions involve large amounts of time spent raising the hands above the head, which can be extremely fatiguing. One example is a
grocery store employee who must repeatedly raise his or her arms overhead with a payload in order to restock shelves. By offloading shoulder adductor muscles, our exomuscle might increase endurance and decrease discomfort during such activities. In addition, our exomuscle could be used to augment the user’s strength.

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