HERCULES: A Three Degree-of-Freedom Pneumatic Upper Limb Exoskeleton for Stroke Rehabilitation*

Martin Burns, *Student Member, IEEE,* Zachary Zavoda, Raviraj Nataraj, *Senior Member, IEEE*,
Kishore Pochiraju, *Senior Member, IEEE*, Ramana Vinjamuri, *Senior Member, IEEE*

Abstract— **This paper outlines the construction, current state, and future goals of HERCULES, a three degree-of-freedom (DoF) pneumatically actuated exoskeleton for stroke rehabilitation. The exoskeleton arm is capable of joint-angle control at the elbow in flexion and extension, at the shoulder in flexion and extension, and at the shoulder in abduction and adduction. In the near future we plan to embed kinematic synergies into the control system architecture of this arm to gain dexterous and near-natural movements.**

Clinical Relevance— **This device can be used as an upper limb rehabilitation testbed for individuals with complete or partial upper limb paralysis. In the future, this system can be used to train individuals on synergy-based rehabilitation protocols.**

I. Introduction

Stroke affects over 750,000 individuals each year, and among the survivors the majority experiences some degree of hemiparesis and require rehabilitation. Stroke occurrence rates continue to climb yearly as well, largely due to the rising mean age of the U.S. population [1]. The prevalence of stroke in the US is expected to increase by 22% by 2030, which will also increase the cost of post-stroke rehabilitative therapy and assisted living expenses. Research shows that, among patients with varying degrees of paralysis, upperlimb function is consistently one of the most desired rehabilitation goals [2]. Robotic systems, particularly in the form of exoskeletons, have made significant progress in recent years towards producing devices that can manipulate a paralyzed patient's arm in order to conduct rehabilitative procedures. These procedures have been demonstrated to match or even improve on rehabilitation outcomes, and allow a physical therapist to treat a greater number of patients at once [3].

Exoskeletons are not new to the field of rehabilitative robotics and come in many varieties. Of the documented exoskeletons used thus far for rehabilitative purposes, approximately 70% are powered using some sort of electric drive. Electric drive exoskeletons are accurate and well understood, but can be prohibitively expensive or heavy. In contrast, pneumatic exoskeletons, which comprise a much smaller fraction of documented rehabilitative exoskeletons, offer a high force-to-weight ratio which is desirable for a potentially mobile rehabilitative exoskeletal system. In addition, they can be stopped under a load without causing damage to the system or patient, and require less maintenance than a traditional electric drive system [3].

Available pneumatic exoskeletons use either pneumatic muscles or pneumatic cylinders as actuators. Pneumatic muscles are utilized in the 7 degree-of-freedom (DoF) pneumatically actuated exoskeleton robot by Tsagarakis and Caldwell. This system uses pneumatic muscles mounted antagonistically for actuation and uses torque feedback for joint proportional-integral-derivative (PID) control. The antagonistic muscle configuration allows for "soft-touch", more human-like grasps [4]. The device for robotic assisted upper extremity repetitive therapy (RUPERT) is another rehabilitative pneumatic exoskeleton actuated by pneumatic muscles. RUPERT has 4 DoF and is driven by pneumatic muscles at the elbow, shoulder, and wrist. RUPERT is unique in that it can provide real-time assessment of a patient's functional improvement [5]. The biomimetic orthosis for neurorehabilitation (BONES) also has 4DoF, but in contrast to RUPERT it operates using traditional pneumatic cylinders. BONES, developed at the University of California Irvine, is large and not portable, but offers very high accuracy in replicating upper-limb rehabilitative movements [6]. Other pneumatic exoskeletons are available that use either pneumatic muscles or pistons.

Difficulties with pneumatic control have been well documented by research teams that have attempted pneumatic exoskeletons in the past. Pneumatic actuators, while cheaper and lighter than traditional electric drives, offer unique design challenges in their operation. Due to the compressibility of air and the nature of pneumatic systems, fine, accurate positional control is more difficult with a pneumatic air cylinder, which equates to a less accurate rehabilitation exoskeleton. This has been counteracted through the use of unconventional control schemes or additional pneumatic components [3]. Pneumatic orifices, which control flow rate, and solenoid valves, which control flow direction, are often used in tandem for great effect in pneumatic exoskeletons. Additionally, companies have recently brought to market products like the Festo MPYE line of proportional directional control valves. These valves combine the benefits of a pneumatic orifice and solenoid valve

*Research supported by the National Science Foundation (NSF) CAREER Award CHS-1845197.

M. Burns, Z. Zavoda, R. Nataraj, and R. Vinjamuri are with the Department of Biomedical Engineering, Stevens Institute of Technology, Hoboken, NJ, 07030, USA (e-mail: ramana.vinjamuri@stevens.edu).

K. Pochiraju is with the Department of Mechanical Engineering, Stevens Institute of Technology, Hoboken, NJ 07030, USA.

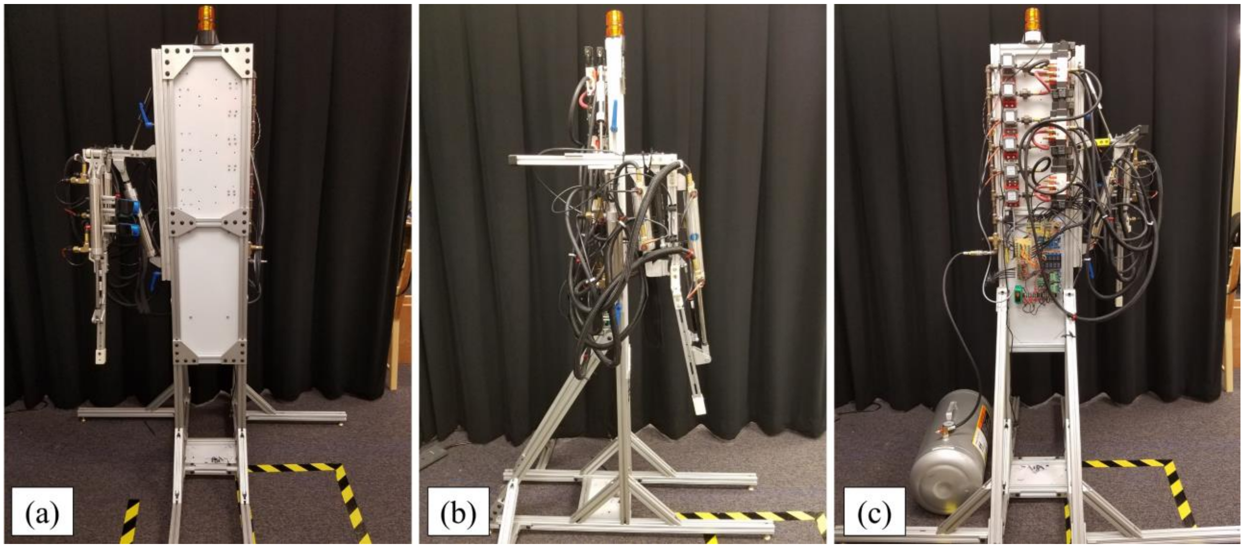

Figure 1. Front (a), right (b), and back (c) views of the HERCULES arm. The arm assembly is mounted on a vertical slide that can adjust to accommodate any subject height in a standing or seated position, and a wheelchair can be positioned within the system.

in one package, significantly reducing weight and complexity of a system.

The HERCULES arm, Fig. 1, is a three degree-of-freedom pneumatic upper-limb exoskeleton intended for stroke rehabilitation purposes. The exoskeleton is driven by three dual-acting air cylinders. These cylinders are mounted on the arm in such a way that the exoskeleton arm is capable of shoulder abduction, shoulder flexion, and elbow flexion. The arm is also adjustable to fit a wide range of potential patients, and is designed to be wheelchair accessible. The air cylinders are controlled via a LabVIEW virtual instrument (VI) running Proportional-Integral (PI) control algorithms. Air pressure and direction control are provided via a series of solenoid valves and pneumatic orifices, and all pressure readings are taken at the air cylinder inlets through in-line pressure transducers. All on-system components are controlled via an Arduino Mega2560 microcontroller.

II. Design

A. Mechanical Design

The exoskeleton's structure was constructed out of 2.54cm (1 inch) and 3.81cm (1.5 inch) square 80/20 aluminum extrusion (Fig. 2). The exoskeleton is free-standing and has metal feet for stability. The actual arm-manipulator component is mounted on the right side of the exoskeleton frame, which limits the use of the exoskeleton to patients suffering hemiparesis of the right arm exclusively. The arm-manipulator is adjustable in the posterior/anterior direction and superior/inferior direction in order to accommodate a larger range of patients. The anterior/posterior direction adjustment is to accommodate for joint alignments and variations in wheelchair designs. Patients can operate the exoskeleton in either sitting or standing positions, and the frame was designed such that a wheelchair bound patient could comfortably operate the device.

The patient's arm is affixed to the HERCULES arm manipulator at two points: the middle-forearm and the upper arm. The forearm padded orthotic brace can slide 5.08cm (2 inches) distally to account for variations in arm lengths, and can adjust in circumference in order deal with different arm widths. Additionally, the arm-manipulator is built with mounting points in order to handle future expansions in the realm of active hand-manipulation exoskeletons.

B. Pneumatic Design

Three Bimba brand dual-acting air cylinders are mounted on the arm-manipulator and provide all actuation to the HERCULES Arm. These cylinders, the MRS-177-DXP-00ML, MRS313-DXP-00ML, and MRS-317-DXP-00MC (Bimba, University Park, IL), are mounted in analogous positions to the biceps brachii, triceps brachii, and trapezius muscles respectively. The biceps analogous cylinder controls elbow flexion and extension, and triceps analogous cylinder controls shoulder flexion and extension, and the trapezius analogous cylinder controls shoulder abduction and adduction. Fig. 2 illustrates the current pneumatic and structural arrangement. These dual-acting air cylinders provide all of the power for manipulation of the exoskeleton and are controlled by pneumatic orifices and solenoid valves.

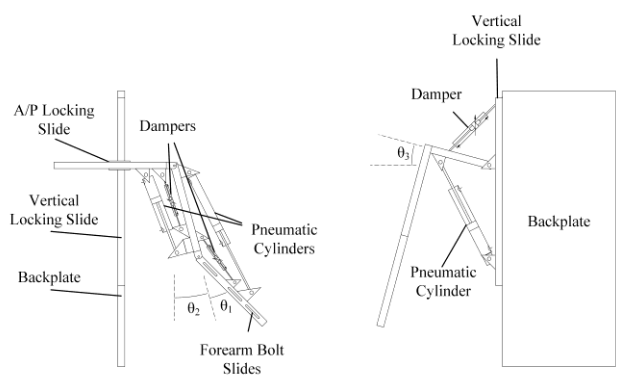

Figure 2: HERCULES structure, with major components labeled. Elbow flexion/extension (θ_1), shoulder flexion/extension (θ_2), and shoulder abduction (θ_3) are each actuated by a pneumatic cylinder and viscous damper. The vertical locking slide allows height adjustment of the exoskeleton, and the anterior-posterior locking slide allows front/back adjustment to align with the subject's shoulder center of rotation.

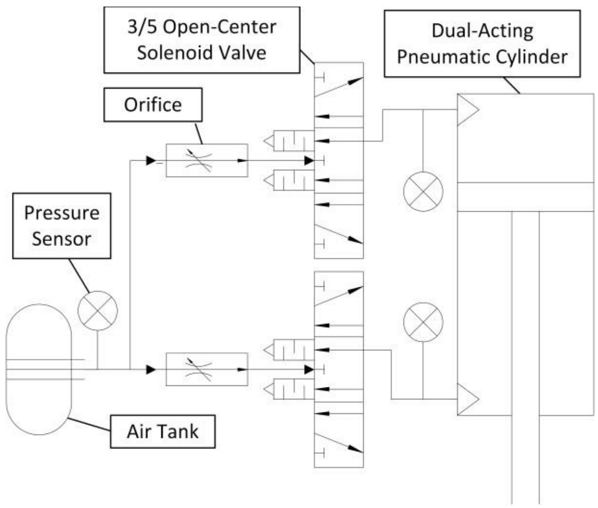

Figure 3: Pneumatic diagram for one actuator. The pressure in each chamber of the dual-acting pneumatic cylinder is regulated by a pair of electronic orifices and solenoid valves. Chamber and supply pressures are monitored by dedicated analog pressure sensors.

Cylinder pressure is controlled by a series of Type 500x E/P Transducer pneumatic orifices (Controlair Inc., Amherst, NH) and Nitra AVS-53 5/3 normally open solenoid valves (AutomationDirect, Cumming, GA). Two solenoid valves work in tandem with two orifices for each dual-acting cylinder in order to provide different pressures on each side of the cylinder. PX3AN1BH pressure transducers (Honeywell, Morris Plains, NJ) are mounted at the inlets on both sides of the dual-acting cylinders and provide pressure data for the control systems with a 10-100 PSI operating range. Additionally, a Wika Model A-10 pressure transducer (Wika, Lawrenceville, GA) is mounted at the air tank hookup location in order to read a global system pressure. Fig. 3 illustrates the pneumatic configuration for one dual-acting cylinder. This configuration is mirrored for all actuators. The system is designed to operate at a system pressure of 40 to 90 psi. All pressure sensors are calibrated against a NIST-certified digital pressure gauge (SSI Technologies Inc, Janesville, WI, USA).

C. Electrical Design

The HERCULES Arm is controlled by an Arduino Mega2560x microcontroller (Arduino LLC) with its own dedicated power supply. Fig. 4 is an electrical schematic outlining the process by which one of the actuators is controlled. This process is replicated for the other two actuators. As previously mentioned, the Arduino controls all relays and PWM outputs. Additionally, the Arduino is being used as the data acquisition (DAQ) device, and all sensors and transducers terminate at the Arduino. All of this information is then sent to a computer running a custom LabVIEW virtual instrument (VI) which displays all relevant information and provides the user with the exoskeleton's controls.

The pressure sensors and potentiometers return linear 0-5V analog signals to the Arduino Mega. The solenoid and orifice pneumatic components are controlled by 5v relays and pulse-width-modulation (PWM) to 0-10v converters respectively. Twelve HK3FF-DC5VSHG 5v relays (Huike Electronics, Shenzhen, China) control all of the pneumatic solenoids. The relays operate in pairs and are triggered by an Arduino Mega2560; one relay in the pair opens the solenoid to release air into the cylinder, the other relay vents air from the cylinder, and when both are triggered the solenoid valve closes the air path to the cylinder and holds that air captive. The pneumatic orifices are also controlled via an Arduino Mega2560. The Arduino Mega2560 outputs a PWM signal to one of six PWM to 010v conversion circuits which then outputs a 0-10v signal to the orifice. The orifices are configured to open linearly based on the output signal.

D. Safety Features

The HERCULES Arm was designed with patient safety in mind, and as such has built-in safety features to ensure no patient harm. The entire exoskeleton is configured such that,

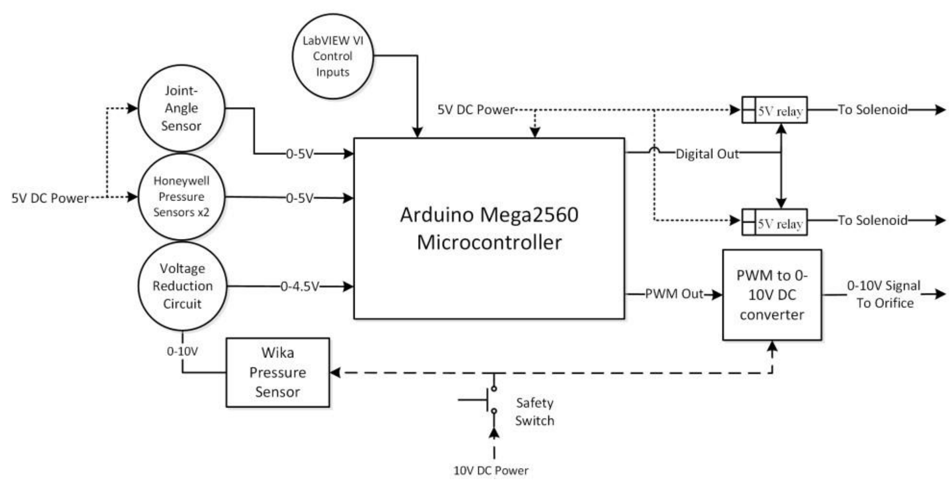

Figure 4: Electrical architecture for one degree of freedom of HERCULES. Power, data, and control signals are outlined along with key electrical components. An Arduino MEGA 2560 reads voltages from the supply pressure sensor, chamber pressure sensors, and joint angle potentiometers which are calibrated against ground truth pressures and angles. Movement commands from LabVIEW are converted to digital solenoid commands and PWM orifice commands.

in the event of power loss, the pneumatic orifices will fully open and vent all system pressure. In the event of an emergency venting situation, the system is then slowly returned to rest by three ACE mechanical dampers mounted parallel to the air cylinders. Additionally, the system will only operate when a normally-off safety button is depressed. This switch is intended to be operated by the user, and if the user elects to stop depressing the button the system will begin the previously mentioned emergency venting. The switch is designed to only cut power to the pneumatic system, which prevents a full system reboot every time the switch is released.

III. Discussion

The HERCULES Arm as it stands is a prototype which aims to be a wheelchair-mounted assistive exoskeleton. In its current state, the mechanical assembly and associated pneumatic and electrical components are robust enough to move forward with dynamics modeling, control system design, and kinematic and dynamic validation testing.

The 3 DoF HERCULES exoskeleton is a good candidate for the embedding of kinematic synergies. Kinematic synergies [7, 8, 9] are movement primitives that are observed in joint movement kinematics. It is hypothesized that the brain, an intelligent controller, could control synergies to handle complex movements instead of controlling in joint space. Recent studies in biomimetic control systems have incorporated postural grasp synergies into robotic and prosthetic manipulators [10, 11, 12]. This work on control using postural synergies was extended to include spatiotemporal synergies in hand prosthetics [13]. Additionally, modifications to the mechanical assembly will be made to allow for future expansions and compatibility with hand exoskeletons currently in development, such as the HEXOES system [14, 15, 16].

Future steps for the HERCULES Arm system will improve upon various aspects of the project and help quantify system behavior as a whole. A complete dynamic state-space model with a full closed-loop control system will be created and implemented, which will then allow for the inclusion of kinematic-synergy based control architectures. These kinematic synergies will then be controlled with human biosignals or user controls. When all modifications are made, final verification without and with healthy occupants will occur. When verification is completed, recruiting of affected subjects for rehabilitation trials can begin. The 3 DoF design is limited compared to the DoF of the natural shoulder and elbow, however this architecture is sufficient to get preliminary results on synergy-based upper limb rehabilitation. These results can then justify further iteration on HERCULES to include more DoF.

IV. Conclusion

The preliminary design of the HERCULES Arm, a 3 DoF pneumatic exoskeleton intended for rehabilitation, show that the system is a suitable base on which future improvements can occur. Kinematic validation data will be provided with a suitable model-based closed loop controller, allowing agile control movement for rehabilitation. Next, a synergy-based controller can be implemented that drives the system biomimetically, making it a viable testbed for synergy-based rehabilitation methods. The HERCULES system may also be combined with the HEXOES device for grasp assistance.

Acknowledgment

The authors would like to thank the Department of Biomedical Engineering, the reviewers for their valuable feedback, and the Center for Healthcare Innovation for their continued support of our research.

References

[1] G. Kwakkel, B. J. Kollen, and H. I. Krebs, “Effects of robot-assisted therapy on upper limb recovery after stroke: A systematic review,” Neurorehabil. Neural Repair, vol. 22, no. 2, pp. 111–121, 2008.

[2] K. D. Anderson, “Targeting Recovery: Priorities of the Spinal Cord-Injured Population,” J. Neurotrauma, vol. 21, no. 10, pp. 1371–1383, 2004.

[3] R. A. R. C. Gopura, D. S. V. Bandara, K. Kiguchi, and G. K. I. Mann, “Developments in hardware systems of active upper-limb exoskeleton robots: A review,” Rob. Auton. Syst., vol. 75, no. April 2016, pp. 203–220, 2016.

[4] N. G. Tsagarakis and D. G. Caldwell, “Development and control of a ‘soft-actuated’ exoskeleton for use in physiotherapy and training,” Auton. Robots, vol. 15, no. 1, pp. 21–33, 2003.

[5] T. G. Sugar, J. He, E. J. Koeneman, J. B. Koeneman, R. Herman, H. Huang, R. S. Schultz, D. E. Herring, J. Wanberg, S. Balasubramanian, P. Swenson, and J. A. Ward, “Design and control of RUPERT: A device for robotic upper extremity repetitive therapy,” IEEE Trans. Neural Syst. Rehabil. Eng., vol. 15, no. 3, pp. 336–346, 2007.

[6] J. Klein, S. J. Spencer, J. Allington, K. Minakata, E. T. Wolbrecht, R. Smith, J. E. Bobrow, and D. J. Reinkensmeyer, “Biomimetic orthosis for the neurorehabilitation of the elbow and shoulder (BONES),” Proc. 2nd Bienn. IEEE/RAS-EMBS Int. Conf. Biomed. Robot. Biomechatronics, BioRob 2008, no. November, pp. 535–541, 2008.

[7] R. Vinjamuri, M. Sun, C.-C. Chang, H.-N. Lee, R. J. Sclabassi, and Z.-H. Mao, “Dimensionality Reduction in Control and Coordination of the Human Hand,” IEEE Trans. Biomed. Eng., vol. 57, no. 2, pp. 284–295, 2010.

[8] R. Vinjamuri, D. J. Weber, Z. H. Mao, J. L. Collinger, A. D. Degenhart, J. W. Kelly, M. L. Boninger, E. C. Tyler-Kabara, and W. Wang, “Toward synergy-based brain-machine interfaces,” IEEE Trans. Inf. Technol. Biomed., vol. 15, no. 5, pp. 726–736, 2011.

[9] M. K. Burns, V. Patel, I. Florescu, K. V. Pochiraju, and R. Vinjamuri, “Low-Dimensional Synergistic Representation of Bilateral Reaching Movements,” Front. Bioeng. Biotechnol., vol. 5, no. February, pp. 1–15, 2017.

[10] T. Wimböck, B. Jahn, and G. Hirzinger, “Synergy level impedance control for multifingered hands,” IEEE Int. Conf. Intell. Robot. Syst., pp. 973–979, 2011.

[11] J. Rosell, R. Suárez, C. Rosales, and A. Pérez, “Autonomous motion planning of a hand-arm robotic system based on captured human-like hand postures,” Auton. Robots, vol. 31, no. 1, pp. 87–102, 2011.

[12] G. C. Matrone, C. Cipriani, M. C. Carrozza, and G. Magenes, “Real-time myoelectric control of a multi-fingered hand prosthesis using principal components analysis,” J Neuroeng Rehabil, vol. 9, p. 40, 2012.

[13] M. K. Burns, D. Pei, and R. Vinjamuri, “Dynamic Control of Virtual Hand Grasp Using Spatiotemporal Synergies,” IEEE Access, vol. 7, no. 1, pp. 112327–112338, 2019.

[14] M. K. Burns, K. Van Orden, V. Patel, and R. Vinjamuri, “Towards a wearable hand exoskeleton with embedded synergies,” Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc. EMBS, pp. 213–216, 2017.

[15] M. Burns, D. Pei, and R. Vinjamuri, “Myoelectric Control of a Soft Hand Exoskeleton Using Kinematic Synergies,” IEEE Trans. Biomed. Circuits Syst., vol. 13, no. 6, pp. 1351–1361, 2019.

[16] M. Burns and R. Vinjamuri, “Design of a soft glove-based robotic hand exoskeleton with embedded synergies,” in Advances in Motor Neuroprosthesis, R. Vinjamuri, Ed. Springer, 2019.