2020 8th IEEE International Conference on Biomedical
Robotics and Biomechatronics (BioRob)
New York, USA. Nov 29 - Dec 1, 2020

A Theoretical Framework for a Network of Elastic Elements Generating Arbitrary Torque Fields

Partha Ryali,[1] Tommasso Carella,[2] Daniel McDermed,[3] Victoria Perizes,[4] Felix Huang,[5] and James Patton[1]

***Abstract*— Diagonal spring elements can render torque to any orthotic joint, and here we describe the theoretical framework for an ExoNET device that utilizes stacked spring elements as torque generators. Stacked spring elements act mathematically as basis functions, which can be simultaneously tuned to deliver any torque-angle relation. Here we outline the theory, demonstrate our initial developments in several example applications, and then describe the design considerations necessary to develop a functional prototype. We show several exemplary solutions: replicating the torque-angle profile of a single muscle (brachioradialis), two-joint gravity compensation for arm weight, error augmentation and limit push fields capable of providing forces for rehabilitation, and attractor torque fields that collectively pull the arm towards a desired position. This ExoNET system has the potential to be quickly and inexpensively constructed and easily configured by the end user or clinician for specific needs. It shifts control intelligence from the software to physical hardware, which is an efficient solution for neurorehabilitation, military, manual labor, and performance enhancement.**

I. Introduction

Simple exoskeletons have been used for several years as assistive and therapeutic tools for regaining motor control during rehabilitation. These devices employ a wide variety of modalities for torque generation at a joint, with each method holding its own unique advantages in human-robot interaction. Passive devices able to control joint torque stiffness by the use of tension elements, moment arm adjustments, or mechanical reconfiguration have the potential to be simple, lightweight, non-intimidating, and inexpensive - all of which are sought-after advantages in the design of robots [13].

The MARIONET (Moment Arm Adjustment for Remote Induction of Net Effective Torque) is one such device which utilizes cables and moment arm manipulation to effectively generate torque in upper extremity motion [10]. It belongs to a class of devices that use diagonal tension elements to exert torque on a joint. It varies the moment arm to control torque, rather than regulating the tension. It alters the moment arm by shifting the line of action of the tension element (often rotating it's attachment along a circular path).

This type of design can be useful for actuating an exoskeleton [12], providing gravity assistance for mobility [6], assisting the arm during therapy [7] or simply reducing the metabolic cost of walking [2]. Moment arm adjustments can provide both positive and negative torque by moving to both sides of the joint's center of rotation [9]. By placing spring origins in differing positions relative to the center of rotation, a variety of torque fields are possible that include unstable and even catastrophic phenomena [9].

A MARIONET can be an exo-tendon device, shedding the need for a rigid skeleton and instead relying on the underlying structure of the human operator. Such aspects make this design 'soft' and bring with it the advantages of being user-friendly, safe, and low cost. Moreover, we focus here on adjustable spring tension elements that eliminate the need for motors and controllers. What is required is to have such hardware embody the intelligence that was formerly found in the software.

To address this, we recognize that a clear strength of such a design is its inherent sinusoidal torque profile, whose phase and intensity can be adjusted simply by locating proper attachment points. Because of this flexibility, it is possible to use *multiple* MARIONETs, each mathematically used as a basis function. By combining the torques of these elements in parallel (i.e., stacking MARIONETs) one can approximate any torque function by a linear sum of the contribution of elements, much like a finite Fourier series or a radial basis function network. Essentially, this becomes a methodology to construct multi-joint spring.

Here, we present the theoretical framework and preliminary design considerations for a device we are terming the ExoNET, an Exoskeletal Network for Elastic Torque. Compared to the original MARIONET device which consisted of only a single, adjustable tension element, the ExoNET features multiple tension elements, leading to a greater customizability in generated torque profiles. As the approach is developed, this mechanism has the scale-ability to work across multiple joints while still being user friendly. We present the theory, then demonstrate by revealing progressively more layers of complexity of this application, and then finally speculate on how placing such intelligence in the mechanical hardware will lead to practical clinical solutions.

II. Methods

A. Model Development

Spring elements are the primary torque generators in the ExoNET. Torque (τ) for the spring element is a product of the spring elements moment arm (ρ) and force (F) as

$$\tau = F \times \rho \tag{1}$$

[1]Partha Ryali is a graduate student in Bioengineering at the University of Illinois at Chicago ryali2@uic.edu
[2]Tommasso Carella tommaso.carella@mail.polimi.it
[3]Daniel McDermed danny.mcdermed@valpo.edu
[4]Victoria Perizes vperizes@gmail.com
[4]Felix Huang is a lecturer in the Department of Mechanical Engineering at Tufts University felix.huang@tufts.edu
[1]James Patton is a Professor of Bioengineering at the University of Illinois at Chicago and a Research Scientist at the Shirley Ryan Ability Lab pattonj@uic.edu

978-1-7281-5907-2/20/$31.00 ©2020 IEEE

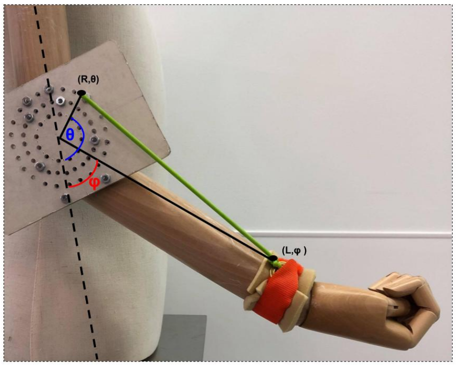

Fig. 1. **Simplified MARIONET ExoNET design** Single Element ExoNET, where by L represents the length of the arm link and R corresponds to the distance between the peg and the center of rotation. θ is the angle for which the peg is located relative to horizontal (dotted black line) and Φ is the angle of the arm link relative to horizontal. In this case surgical tubing acts as a spring element.

The moment arm ρ is governed geometrically by

$$\rho = \frac{LRsin(\theta - \phi)}{\sqrt{R^2 + L^2 - 2RLcos(\theta - \phi)}} \tag{2}$$

and is a function of the spring element's location (attachment point) relative to a joint's center of rotation (R and θ) and the angle of the arm link relative to the horizontal (Φ, Fig. 1). The spring force is most simply governed by Hookes Law with a resting length, x_0,

$$F = -k(x - x_0) \tag{3}$$

but this may be expanded to accommodate nonlinear or other impedance properties.

Since torque deficit profiles tend to be highly complex [5], it is not possible for a single spring element, or a single ExoNET element, to provide the desired torque. However, using combinations of ExoNET elements (what we call ”stacks”) capitalizes on their behavior as basis functions and allows us to sum the torques profile of each element to provide a unique output (Equation 4).

$$\tau_{total} = \sum_{i=1}^{n} \tau_i \tag{4}$$

Here, *n* represents the total number of stacks of elastic elements.

B. Empirical Optimization

We next tested how well this device can approximate a desired torque profile. For this example, we chose a profile that substitutes the torque equivalent to that of the brachioradialis muscle [5], assuming that tension in that muscle is constant. The orthotic goal is to make up for deficits associated with a paretic muscle (see the red dashed lines in Figure 2). We test the ability of the ExoNET to match this desired torque profile, approximated by our single or multiple ”stacked” configuration.

Simple function minimization (MATLAB Optimization toolbox) was used to determine the optimal spring anchor positions, (R) and (θ). Since it is not realistic to anchor a spring at a very large or very small radius, the range of possible radii values was constrained between 0.01 m and 0.15 m. The optimization process aimed to minimize the cost given by the summed squared errors between the desired profile and the one calculated through the ExoNET system.

We next tested the system's ability to optimize a variety of assistive and rehabilitative torque fields in a multi-joint application here, using the elastic elements that cross the shoulder, elbow, and both shoulder and elbow. Using an anthropomorphic model of body segment parameters of geometry and mass distribution of a 50th percentile male [15]. The optimization was broadened to fit all parameters of all elements crossing all joints to minimize the mean square error of torque at a set of positions in the workspace.

III. Results and Discussion

A. Single-element ExoNET System

The optimization process was initially run for a single spring element ExoNET. As shown by Figure 2 (*Upper*), the average error between the single element ExoNET and the desired torque profile is 0.2457 Nm. This demonstrates the single element ExoNET's capability to match the general trend of any desired torque profile.

B. Multi-element ExoNET System

Subsequently, the optimization process was run several times for varying numbers of spring elements stacked together in optimal positions. As shown in Figure 2 (*Lower*), the optimization provides accurate results when there are multiple spring elements stacked together. In fact, the average error between the desired torque profile and a 3-element ExoNET is only 0.014396 Nm. If more than three elements are combined (not shown), the accuracy of the system remains consistent at an average error value of around 0.01. Therefore, we believe that having 3 stacked elements is sufficient for generating any desired torque profile.

C. Multi-joint, Multi-element ExoNET System

As we have observed, a single ExoNET system between two joints is able to provide a host of assistive forces that matches the general trend of any desired torque and a three element ExoNET system is able to provide a highly customized torque profile that can approximate any desired torque (Fig. 2, red vectors). However, an ExoNET that only crosses two joints may be limited in its application to clinical rehabilitation. We believe that if the ExoNET concept is extended to a multi-joint, multi-element ExoNET system, then it is possible to generate a wider range of motion than a two-joint system and has the potential to be utilized in a number of clinical applications (Fig. 1b). This also lends insight into why we may also have two-joint muscles that can make efficient use of elastic strain energy to accomplish torque fields.

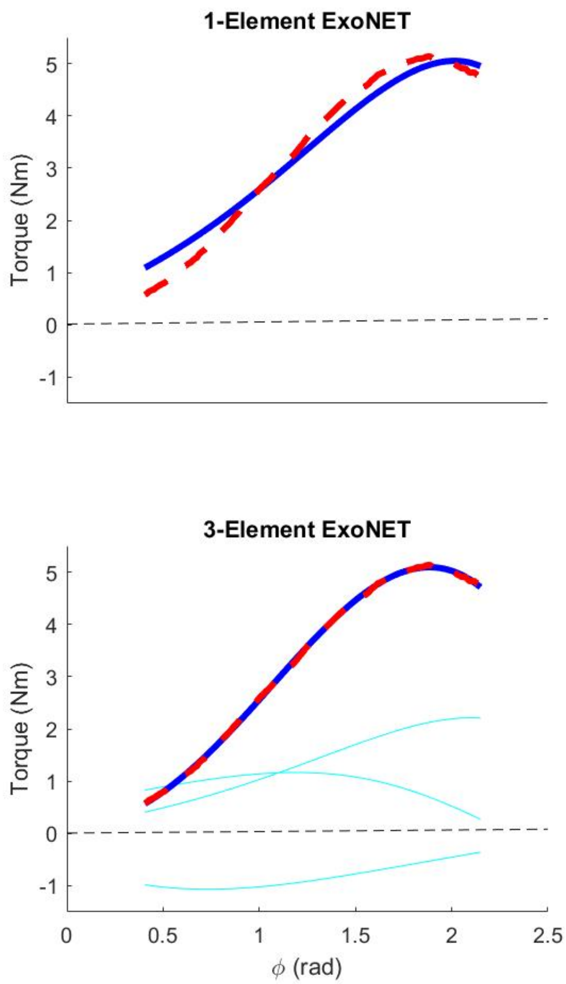

Fig. 2. **Optimization results using the simplest single element (upper) and a three-element (lower) ExoNET**. The results of the optimization process are presented for varying numbers of spring elements on the ExoNET. The desired torque profile is represented in red, the torque profile generated by the optimization is represented in blue, and the torque profiles of the individual spring elements is represented in cyan. Optimization of Single Element ExoNET System. The average error between the desired torque profile and a single element ExoNET system was .24577 Nm, with a variance of .019887 Optimization of Three element ExoNET system. The Average error between the desired torque profile and a three element ExoNET system is 0.08936, with a variance of 0.003919

D. Applications for Assistance

Given the increasing numbers of individuals suffering from physical disabilities, the ExoNET may serve as a potential solution for reducing the metabolic cost of performing activities of daily living by providing assistance to users.

One simple application of the multi-joint, multi-element ExoNET is its ability to provide a field for gravity compensation. This ability was evaluated by providing a weight force and desired torque field to mimic the torque field needed to compensate for the weight of a subject's arm. The optimum torque field generated by the ExoNET (Fig. 3) successfully demonstrated its potential for gravity compensation and warrants further investigation in a clinical setting. The successful results were generated with a single- element, multi-joint ExoNET (single spring element across each of the shoulder-elbow, elbow-wrist, and shoulder-wrist joints).

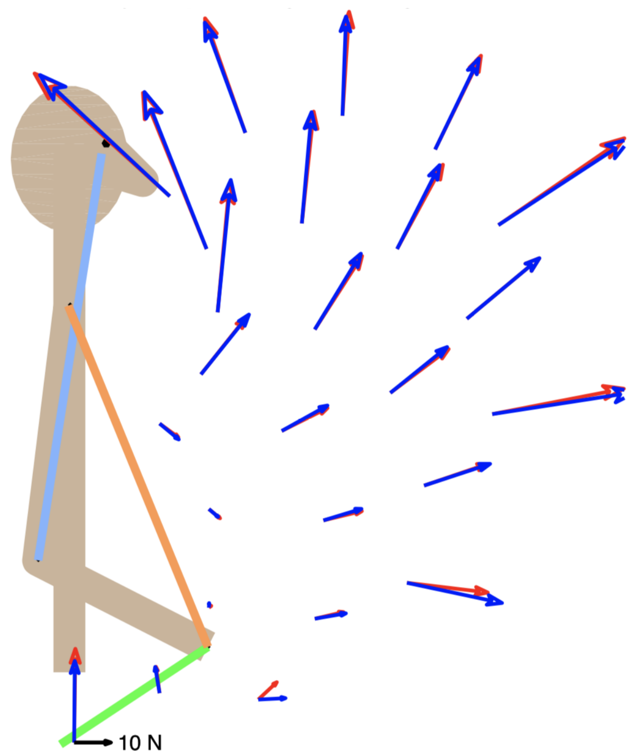

Fig. 3. **Gravity Compensation Field.** The ExoNET's capability for generating a gravity compensation for a 70 kg individual, shown as a vector field, a multi-dimensional display of the effect of the device's compensation at various workspace positions. The field generated by the ExoNET (blue vectors) almost perfectly match the gravitational demand (red vectors). This single element- multi joint ExoNET is able to provide compensation for the weight of the arm.

The ExoNET may also be used to pull an individual's arm to a desired position in a specified workspace. The torque fields necessary for this are known as attractor fields and may be incredibly useful in a number of applications and settings - clinical and industrial. For any task that requires an individual to move their arm to a singular position - brushing teeth, combing hair, opening a door, etc. - may be achieved through a single attractor field. We were able to successfully demonstrate the ExoNET's capability for optimizing single attractor fields (Fig. 4).

E. Applications for Neurorehabilitation

Tunable, unstable spring designs, such as the ExoNET, have the potential to mechanically amplify the errors made by the user. For example, if a user attempts to flex their arm, unstable spring designs may force them to put in more effort towards following the movement path. Such error augmentation has been shown recently to have promising effects on enhancing motor recovery for brain-injured patients suffering from a host of motor deficits [14]. Recent studies on robotic training have also shown the potential for reshaping

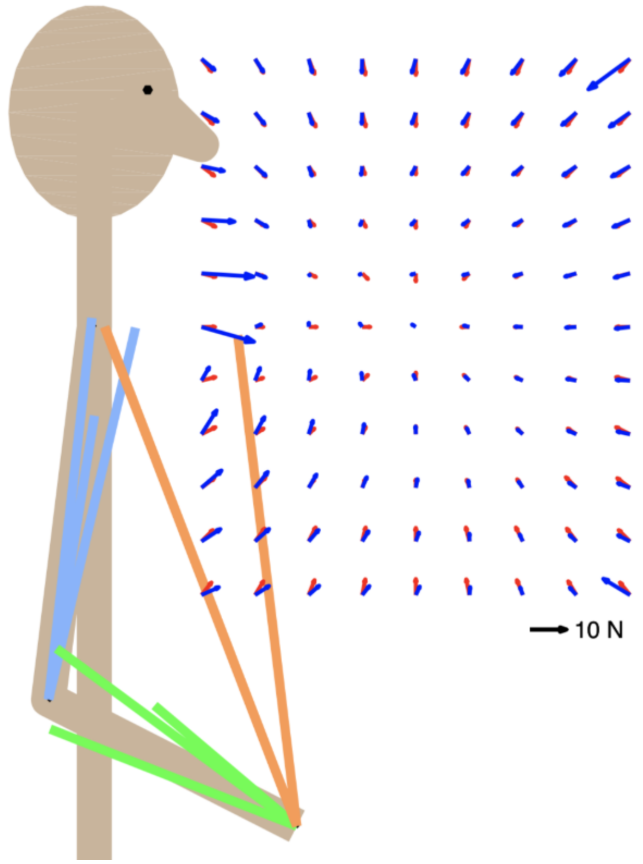

Fig. 4. **Single Attractor Field.** The ExoNET's capability for generating a Singular Attractor Field, shown as a vector field, a multi-dimensional display of the effect of the device's compensation at various workspace positions. The field generated by the ExoNET (blue vectors) matched the desired force vectors (red vectors) of the attractor field with an average error of .02 Nm.

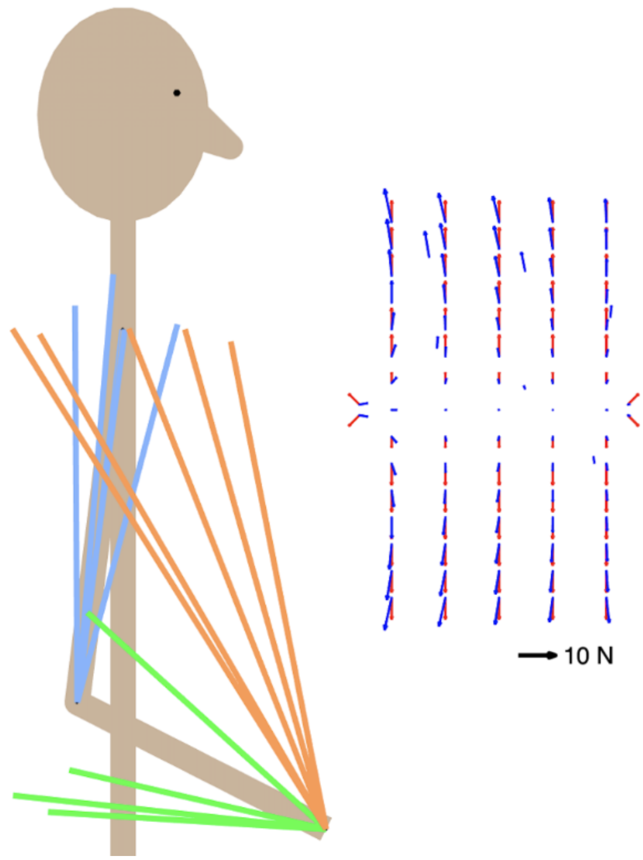

Fig. 5. **Error Augmentation Field.** The ExoNET's capability for generating an error augmentation field, useful in enhanced motor recovery, is visualized as a three-dimensional display of the effect of the device's torque fields at various workspace positions. The field generated by the ExoNET (blue vectors) closely matches desired error augmenting forces (red vectors) with an average error of 0.023 Nm. This five element- multi joint ExoNET is able to successfully simulate error augmentation.

movement trajectories by artificially introducing an unstable, high cost force field known as a limit push field [8]. The limit push field is characterized by a system of disturbance forces surrounding a box shaped region of zero force [4].

We provided a series of Error-Augmenting and Limit Push Forces to the ExoNET system, and evaluated the results of the optimization at varying numbers of "stacks" of spring elements. The optimal torque field generated by a five element, multi-joint ExoNET successfully demonstrated the system's potential for providing an error-augmentation profile with an average error of .023 Nm (as shown in Fig. 5) and a three element, multi joint ExoNET was used to generate a limit-push profile with an average error of .001 Nm (as shown in Fig. 6). A one and two element ExoNET were also tested, however, their respective generated torque fields had a larger error than the three element ExoNET. This is indicative of a need for larger "stacks" of spring elements to generate complex torque fields. In this case, the Error Augmentation profile proved to be more complex for the optimization algorithm.

F. Design Considerations

We determined the design requirements for the ExoNET [3], driven by the need for a lightweight, simple, customizable device that provides any arbitrarily chosen torque profile to multiple joints. Most importantly, the end user for the ExoNET, whether it's a therapist assisting a stroke patient or a factory worker doing manual assembly, should have the ability to easily change the moment arm and resting length of the elastic elements. 3D printing technology offers a cost-effective potential avenue for building a moment arm adjustment mechanism consisting of "levers" or rotators capable of moving around a joint's center of rotation with a series of holes that serve as attachment points for the elastic elements. Cleats at the wrist and elbow joints may also be of use in adjusting the resting length of the elastic elements. Since the ExoNET may be in use for extended periods of time, it's important to focus on designing a device that contains a soft structure that provides comfort to the user [1].

G. Applications for the Lower Extremity

We speculate that similar ExoNET designs have the potential to provide torque fields for any joints amenable to exotendon devices. This should be particularly important in lower extremity, since one of the hallmark consequences for

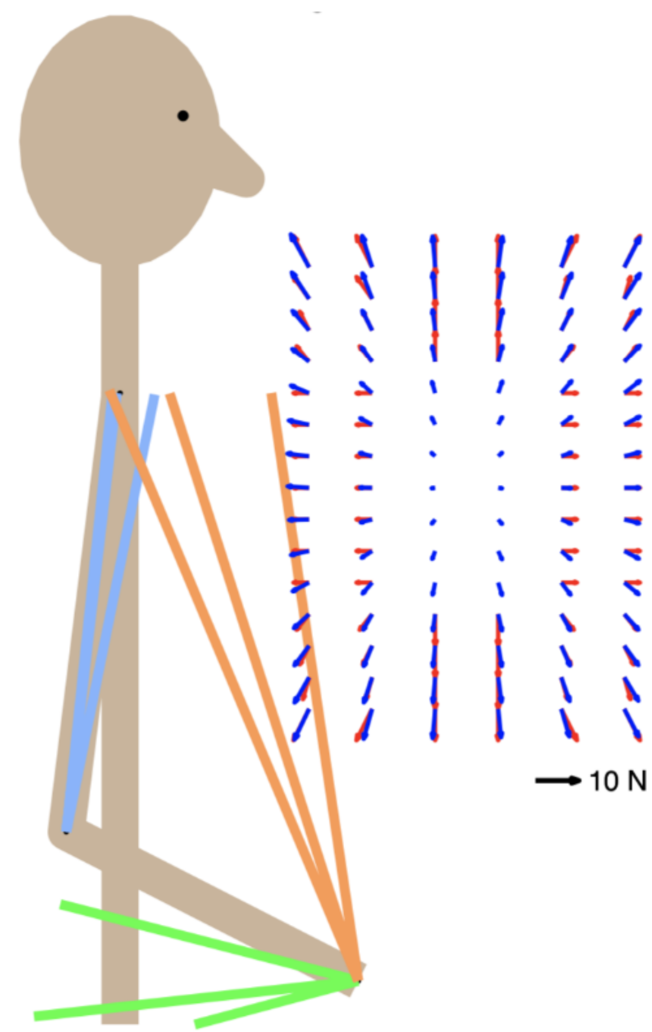

Fig. 6. **Limit Push Field.** The ExoNET's capability for generating a limit push field for neurorehabiliation, is shown at various workspace positions. The field generated by the ExoNET (blue vectors) almost perfectly matches the desired forces for a limit push field (red vectors) with an average error of 0.001 Nm. To achieve this level of accuracy, a three element-multi joint ExoNET was necessary in the simulation

individuals that survive from a stroke is Stiff Knee Gait (SKG), which is characterized by a decrease in knee flexion capability during the swing phase of the gait cycle [11]. As a consequence of SKG, other compensatory methods such as hip hike on the ipsilateral side are developed. This is particularly detrimental as such abnormal gait patterns decrease energy efficiency, rendering the act of walking a taxing and unpleasant facet of life. Currently, our system could allow a therapist to quickly tune each stack to provide the appropriate amount of torque during swing phase for SKG, or any other patients a torque deficit.

IV. Conclusions

The simple expansion of the original MARIONET concept to a combination of diagonal spring elements sheds light on new capabilities for a simple design. The proposed ExoNET now has the potential to be a simple customizable tool capable of providing assistive torques to patients with motor deficits. The motivation behind this device is to allow therapists to easily assemble and adjust the ExoNET depending on an individual patients unique motor deficits. Additionally, our design aims to fit into a large variety of anthropometric dimensions so as to be easily used on a greater number of people. This exotendon network of "stacked" elements has the potential to be used for the actuation of several joints, can deliver non-linear torque fields, allow for stable and unstable configurations and bi-stability, and can even mechanically replace some state-dependent control algorithms. This represents a shift of the intelligent aspects of control from the software programs to the physical hardware, which may be a sleek, economical solution for actuator designs that advance human neurorehabilitation technology.

V. Acknowledgements

This work was supported in part by NIDILRR 90REGE0005-01.

The Authors declare that there is no conflict of interest.

References

[1] Paul Baniqued, Renann Baldovino, and Nilo Bugtai. "Design Considerations in Manufacturing Cost-Effective Robotic Exoskeletons for Upper Extremity Rehabilitation". In: Dec. 2015. DOI: 10.1109/HNICEM.2015.7393198.

[2] Steven H. Collins, M. Bruce Wiggin, and Gregory S. Sawicki. "Reducing the energy cost of human walking using an unpowered exoskeleton". In: *Nature* (2015). ISSN: 14764687. DOI: 10.1038/nature14288. arXiv: 15334406.

[3] Michele Folgheraiter et al. "Design of a Bio-Inspired Wearable Exoskeleton for Applications in Robotics." In: Jan. 2009, pp. 414–421.

[4] E. Hajissa, A. Shah, and J. L. Patton. "Visual Limit-Push Training Alters Movement Variability". In: *IEEE Transactions on Biomedical Engineering* 65.10 (Oct. 2018), pp. 2162–2167. ISSN: 1558-2531. DOI: 10.1109/TBME.2017.2786142.

[5] Wendy M. Murray, Scott L. Delp, and Thomas S. Buchanan. "Variation of muscle moment arms with elbow and forearm positio Pn". In: *Journal of Biomechanics* (1995). ISSN: 00219290. DOI: 10.1016/0021-9290(94)00114-J.

[6] T Rahman et al. "A body-powered functional upper limb orthosis." In: *Journal of rehabilitation research and development* 37.6 (2000), pp. 675–80. ISSN: 0748-7711. URL: http://www.ncbi.nlm.nih.gov/pubmed/11321003.

[7] Robert J. Sanchez et al. "Automating arm movement training following severe stroke: Functional exercises with quantitative feedback in a gravity-reduced environment". In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* (2006). ISSN: 15344320. DOI: 10.1109/TNSRE.2006.881553.

[8] A. K. Shah et al. “Reshaping Movement Distributions With Limit-Push Robotic Training”. In: *IEEE Transactions on Neural Systems and Rehabilitation Engineering* 26.11 (Nov. 2018), pp. 2134–2144. ISSN: 1558-0210. DOI: 10.1109/TNSRE.2018.2839565.

[9] James S. Sulzer, Michael A. Peshkin, and James L. Patton. “Catastrophe and stability analysis of a cable-driven actuator”. In: *Annual International Conference of the IEEE Engineering in Medicine and Biology - Proceedings*. 2006. ISBN: 1424400325. DOI: 10.1109/IEMBS.2006.260514.

[10] James S. Sulzer, Michael A. Peshkin, and James L. Patton. “Design of a mobile, inexpensive device for upper extremity rehabilitation at home”. In: *2007 IEEE 10th International Conference on Rehabilitation Robotics, ICORR’07*. 2007. ISBN: 1424413206. DOI: 10.1109/ICORR.2007.4428535.

[11] James S. Sulzer et al. “Preswing knee flexion assistance is coupled with hip abduction in people with stiff-knee gait after stroke”. In: *Stroke* (2010). ISSN: 00392499. DOI: 10.1161/STROKEAHA.110.586917.

[12] Ronald Van Ham et al. “MACCEPA, the mechanically adjustable compliance and controllable equilibrium position actuator: Design and implementation in a biped robot”. In: *Robotics and Autonomous Systems* (2007). ISSN: 09218890. DOI: 10.1016/j.robot.2007.03.001.

[13] B. Vanderborght et al. “Variable impedance actuators: A review”. In: *Robotics and Autonomous Systems* (2013). ISSN: 09218890. DOI: 10.1016/j.robot.2013.06.009.

[14] Yejun Wei et al. “Visual error augmentation for enhancing motor learning and rehabilitative relearning”. In: *Proceedings of the 2005 IEEE 9th International Conference on Rehabilitation Robotics*. 2005. ISBN: 0780390032. DOI: 10.1109/ICORR.2005.1501152.

[15] David A. Winter. *Biomechanics and Motor Control of Human Movement: Fourth Edition*. 2009. ISBN: 9780470398180. DOI: 10.1002/9780470549148. arXiv: arXiv:0712.2824v3.