2024 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)
October 14-18, 2024. Abu Dhabi, UAE

Seven Benefits of Using Series Elastic Actuators in the Design of an Affordable, Simple Controlled, and Functional Prosthetic Hand

Erfan Koochakzadeh[1], Alireza Kargar[1], Parsa Sattari, Diba Ravanshid, and Rezvan Nasiri*

***Abstract*— This paper highlights the benefits of using series elastic actuators (SEA) in designing a cost-efficient, easily controlled, and functional prosthetic hand. The designed 3D-printed hand uses only two motors in an antagonistic configuration, transferring power to the fingers via pulleys, cables, and springs; i.e., the motors are in an SEA configuration with the load/fingers. In the designed underactuated prosthetic hand, the thumb is adjustable for various tasks, and the optimization of pulley diameters ensures synchronized finger movement during hand flexion and extension. Thanks to the SEA configuration of the motors and fingers, simple position control of the motor enables features like hand position control, morphological grasp, force control, impedance control, slippage detection, safe interaction, and efficient grasp. An extensive set of experiments has been conducted to evaluate the designed prosthetic hand's performance. The experiments confirm the hand's satisfactory performance while also highlighting the importance of improving the proposed design in different aspects. To attain better position control and morphological grasp, minimizing the cable-body and joint friction is recommended. A higher resolution of the current/torque sensor is needed for the precise force control and slippage detection. Finally, a motor brake system is required to achieve efficient grasping.**

***Index Terms*— Prosthetic Hand, Cost Efficiency, Series Elastic Actuator, Control Simplification, Functional Prosthetic Hand**

I. INTRODUCTION

It has been reported that the population of amputees in the United States alone exceeded 1.6 million in 2005, and it is estimated that this number will be more than twice by 2050 [1]. Approximately 10% of the mentioned population is attributed to hand amputations, which can be caused by various factors, including accidents or different health issues such as trauma, malignancy, vascular disease, congenital deformities, and infection [2]. The impact of hand amputation on individuals is profound, often necessitating career changes that adversely affect their daily lives and overall happiness [3]. Accordingly, numerous efforts have been made to design fully functional prosthetic hands to help amputee individuals [4]. However, the current commercial products, such as the Bebionic hand [5] enhanced by myoelectric interface [6], come with a relatively high price, ranging from $10,000 to $40,000, which is not affordable for most of amputees, who are low-income laborers [7].

The commercial prosthetic hands are augmented by myoelectric interfaces to map electromyography (EMG) signals to the corresponding motion, but despite the researchers' dreams, the myoelectric interfaces are still utilized as a trigger switch rather than an advanced EMG decoding system [4], [6], [8]. EMG signals are time-varying, subject-correlated, complex, prone to noise, and unreliable, which limits their applications in laboratory settings and makes them impractical for daily usage [8], [9]. As a result, certain commercial products share the prosthetic hand's control burden with the amputee's intact hand, which mostly interrupts the functionality of the other hand and brings an additional cognitive load for the amputee individuals. In addition, for double-hand amputee individuals, the employment of this technique seems unattainable. Considering the aforementioned challenges, many amputees abandon using myoelectric prosthetic hands [10]. Therefore, adding the myoelectric interface to the existing commercial prosthetic hands only increases their cost without improving their functionality [11]. To resolve this issue, a simple-controlled prosthetic hand is required to minimize the reliance on the myoelectric interface; see [12-15] as our studies on reducing the number of EMG sensors for human-in-the-loop applications.

A solution to design a simple-controlled, affordable, and functional prosthetic hand is integrating cable-driven mechanisms and the Series Elastic Actuators (SEA) concept. The cable-driven mechanisms are underactuated systems that can minimize the number of actuators, which leads to a cost-efficient and simple-controlled design; see [16], [17]. Besides, SEA is a favorable robotic concept [18], specifically in grippers' design [19] due to its unique features in energy efficiency [20], force control [21], safety, impedance regulation [22], and external disturbance rejection [23].

In this paper, we design an affordable prosthetic hand with only two motors and a simple control system, which can provide features like position control, morphological grasp, force control, impedance control, slippage detection, safe interaction, and efficient grasp. The prosthetic hand design, control schematic, and design advantages are presented in Section II. The experiments and results are presented in Section III and the uploaded Video File[1]. Finally, the discussions and conclusions are presented in Section IV.

II. METHODS

This section starts with the problem statement, where we describe a real grasp scenario and count the important

---

This work is based on research funded by the Iran National Science Foundation (INSF) under project No.4020634.

All authors are with the Research Institute for Robotics, Artificial Intelligence, and Information Science (RAIIS), Control and Intelligent Processing Center of Excellence (CIPCE), School of Electrical and Computer Engineering, College of Engineering, University of Tehran, Tehran, Iran.

[1] These authors contributed equally.

* Corresponding author and principal investigator: rezvan.nasiri@ut.ac.ir.

[1] https://www.youtube.com/watch?v=KZ2Mu9mEVGQ

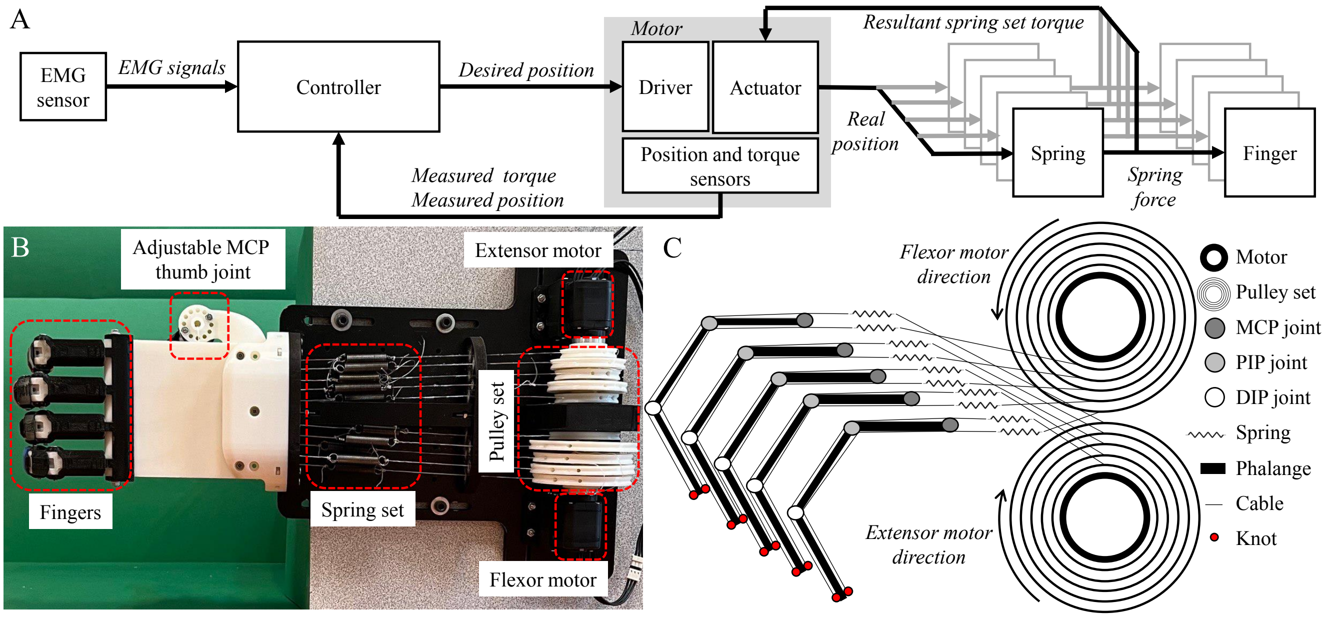

Fig. 1: **The prosthetic hand's control diagram, setup, and power transmission system schematic; i.e., SEA realization.** (A) In this control block diagram, the controller receives the user's EMG signal, the motor's measured position, and the motor's measured torque and accordingly regulates the motor position to perform the grasping task. The motor's real position changes the spring length and consequently regulates the force(torque) applied to the object(motor). The motor driver is responsible for changing the motor position to the desired position. (B) The prosthetic hand setup consists of fingers, an adjustable thumb MCP joint, a spring set, a pulley set, an extensor motor, and a flexor motor. The springs' coefficient and rest length are $0.222N/mm$ and $20mm$, the motors are Dynamixel AX12+, the setup microcontroller is Arduino Mega 2560, and the sum of fingers and palm weights is about $300gr$. The whole setup is 3D printed with PLA material. (C) The power transmission part transmits power through the pulley and spring sets to control the finger movements, where all extensor(flexor) cables are connected to the extensor(flexor) motor.

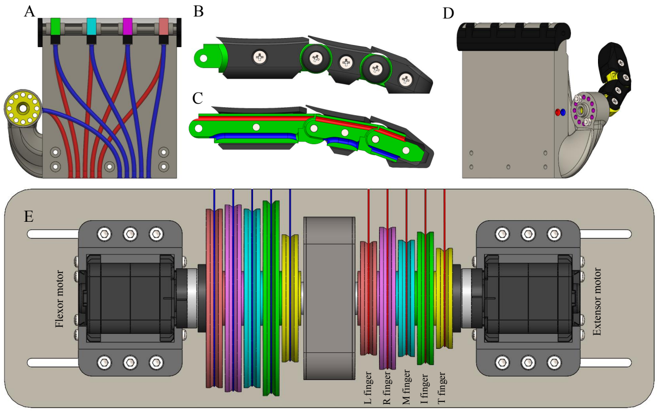

Fig. 2: **The prosthetic hand's detailed design.** (A) indicates a transparent view of the palm and the flexor (blue) and the extensor (red) cable tracks. (B, C) illustrate the index finger mechanism, and the flexor (blue) and extensor (red) cable tracks; except for the thumb finger, the fingers have a similar design but different sizes. (D) presents the 3D figure of the palm and thumb finger. Using the considered adjustable mechanism, the thumb finger configuration can be adjusted with respect to the palm. (E) illustrates the pulley sets for flexor (blue) and extensor (red) motors. The pulley diameters are optimized according to each finger size, and due to the asymmetric cable tracks for flexion and extension, the flexor and the extensor pulley diameters are different.

features of a functional prosthetic hand. Next, we present the detailed design of our prosthetic hand to address the features. Finally, we focus on the main advantages of our design.

A. Problem statement

Fig.1 A describes our proposed control schematic of a prosthetic hand. In this block diagram, the controller receives the user commands by EMG signals, the motor's estimated position, and the motor's estimated force/torque and accordingly regulates the motor's desired position, where the desired position is a control command for the motor driver. Consider the case that the user is approaching an object. In this stage, the user should be able to extend the fingers based on the maximum diameter of the object; i.e., *position control*. Similar to the biological hand fingers' synergy, the prosthetic hand should adapt the fingers' arrangement based on the object shape; i.e., *morphological grasp*.

After the grasp, the user can increase the overall force applied to the object; i.e., *force control*. Force control is essential for a proper grasp, considering different objects' weights, strengths, and the friction between the hand and the objects. Assuming that the object is properly picked by controlling the applied force, there is still a chance that external disturbances could disrupt the grasp stability and cause the object to slip, which manifests the importance of *impedance control*. In the face of external disturbances, the prosthetic hand requires a mechanism to instantly inform the user and the controller; i.e., *slippage detection*. The slippage condition can be translated to the user using a bio-feedback system such as vibrotactile; see [6]. *Safe interaction* and *efficient grasp* are also two important features of a compliant prosthetic hand, which are necessary for long-term usage.

B. Prosthetic hand design

To design a cost-efficient and simple-controlled prosthetic hand along with the counted features, the system is designed with a cable-driven mechanism and only two motors for the whole hand. The motors are in an antagonistic configuration to provide the impedance control property [24]. Accordingly, a set of tension springs in the SEA configuration connects all cable-driven fingers to the motors. The overall presented

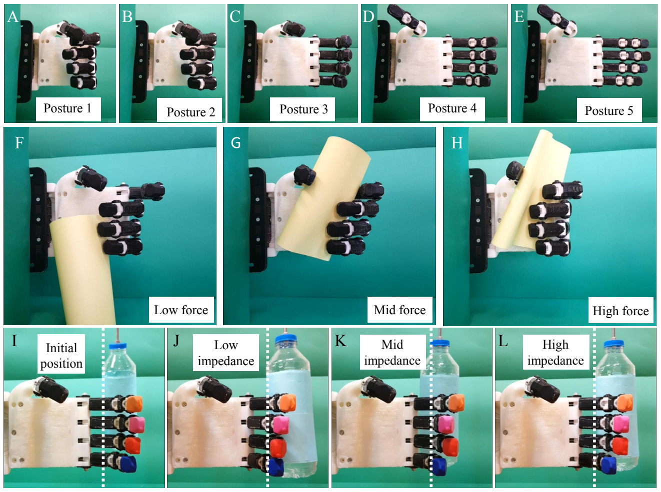

Fig. 3: **The experimental results of position, force, and impedance control.** (A-E) illustrate the position/posture control results in five different postures from fully flexed to fully extended configurations. (F-H) show the force control results on a folded paper with low, mid, and high levels of the applied forces. (I-L) indicates the experimental results for impedance control in four different conditions: (I) is before the bottle hits the hand, and (J-L) are after the bottle hits the hand in low, mid, and high impedance conditions, respectively. The dashed lines are added to provide a visual reference for comparison. The fingertip markers are added to detect the finger motions after the impact/disturbance in the recorded videos.

design includes two main sections: (1) power transmission and (2) motion mechanism; see Fig.2.

1) Power transmission: consists of cables, a pulley set, a spring set, and two motors in an antagonistic configuration; see Fig.1 B, Fig.1 C, and Fig.2 E. The flexor (blue cables) and extensor (red cables) motors' rotations are transmitted to the fingers through the pulley, cables, and spring sets. Due to the different sizes of the fingers, the correspondence pulley diameter needs to be optimized to achieve a coordinated motion among all fingers. In addition, for each finger, due to the asymmetric cable tracks for flexion and extension motions, the flexor and extensor pulley diameters are different; the flexor pulley diameter is larger than its correspondence extensor pulley diameter. It is worth mentioning that considering cam instead of pulley in this design can provide us with more complex hand motions, which is out of the scope of this paper; see [17].

In this design, all of the flexor(extensor) cables are connected to the flexor(extensor) motor; i.e., the motors are in an antagonistic configurations, see Fig.1 C. The flexor(extensor) motor rotation retracts the flexor(extensor) cables, which pulls the flexor(extensor) springs and leads to hand flexion(extension). The springs' coefficient and rest length are selected based on the motor's maximum applied torque and the spring course of motion in the forearm.

2) Motion mechanism: consists of the palm, the fingers, and the forearm; see Fig. 2. The motion mechanism is responsible for the finger motions using the power, transmitted through the cables. The extensor (red) and the flexor (blue) cables are crossed across the palm and knotted to the fingertips; see Fig.2 A and Fig.2 B. The fingers' design is inspired by the Galileo hand [25], and the finger and palm dimensions are optimized according to the biological hand. Except for the thumb, which consists of two phalanges, each of the other fingers has three phalanges. The cables at each finger are protected by a cover, which also prevents the distal interphalangeal (DIP) and proximal interphalangeal (PIP) joints from extra extension; see Fig.2 B. The palm is also equipped with a mechanical lock to limit the extra extension of metacarpophalangeal (MCP) joints. In addition, the external surface of the palm and fingers is covered with a polymer to increase the friction between the object and hand and minimize the slippage chance.

In the palm, a plate is mounted to enable manual rotation of the thumb MCP with a step of 15 degrees. Using this simple mechanism, users can adjust the thumb joint based on the task. All finger joints are equipped with brass bushing to minimize joint friction. The forearm is a wooden part utilized as a base for the power transmission section.

C. Design advantages

1) Position control: In this design, all fingers are connected to motors through cable, spring, and pulley sets (see Fig.1 B), where the pulley diameters are optimized to achieve coordinated motion course between fully extended and flexed hand configurations, when there is no object between the fingers and the palm. Accordingly, in free grasp condition, the motor position control leads to the prosthetic hand position control. Therefore, a user can simply control the whole hand extension based on the object's maximum diameter, using the flexor muscle's activation level.

2) Morphological grasp: Morphological computation is an interesting concept in robotics [26], in which the control system is simplified by increasing the design complexity. This is also an interesting feature of biological systems, in which a group of muscles are controlled by a single control command, i.e., muscle synergy, or the existing biological constraints in the body simplify the controller and minimize the body control cognitive load; e.g., in cases like walking, the task is done without attention. The morphological computation is the intrinsic feature of this prosthetic hand, where due to the spring between the pulley and fingers, the fingers' arrangement is flexible and determined by the object shape; we call this feature morphological grasp, see Fig.4 D-F. This design guarantees the morphological grasp without any EMG signal decoding, and only a flexion command by flexor muscle is required.

3) Force control: One of the main benefits of the SEA is simply switching between the position control and the force control. In this design, the fingers are connected to the motors through the spring set (see Fig.1 C). Consequently, in the free grasp condition, the changes in motor position lead to position control. Nevertheless, in the grasp condition, when the finger positions are fixed, increasing(decreasing) the flexion motor position changes the flexion springs' length and accordingly increases(decreases) the force applied to the object. This feature is essential for a proper grasp to prevent object crush, slippage, and rotation. This can also be simply attained by regulating the activation level of the flexor muscle during the grasp condition.

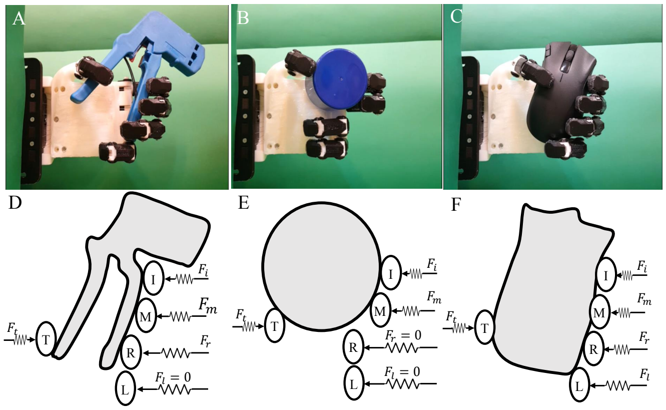

Fig. 4: **The schematic and experimental results for morphological grasp.** (A-C) illustrate the fingers' arrangement for grasping different objects. (D-F) show the conceptual diagram of the morphological grasp and how it is done by the designed prosthetic hand. As it is clear in all figures, due to usage of the SEA, the objects with different shapes are grasped with different fingers' arrangements.

4) Impedance control: Benefiting the impedance control is the main advantage of using antagonistic actuators arrangement for SEA realization. For impedance control, unlike force/position control, in which only one of the motors' positions is changing, both of the motors' positions should be changed such that the hand position/posture and the applied force to the object are almost fixed. Benefiting this feature, provided by motors' antagonistic configuration, the hand position and applied force are fixed, but the grasp posture/position is robust versus external disturbances; see [22]. The user can control the prosthetic hand in the impedance mode by increasing the activation level of the flexor and the extensor muscles at the same time.

5) Slippage detection: During the force control condition, the flexor motor only controls the shaft position. However, the applied torque by the motor is a summation of individual spring forces, which is a function of the fingers' position, and changes according to the object's shape. In slippage conditions, if the fingers' arrangement is changed, the total motor torque will also change, unless the slippage cannot change the fingers' arrangement, which is a rare condition. Besides, in slippage condition, there is an instance that one of the fingers is fully released, consequently the motor's total torque faces an instant change; see Fig.5 A-C. Hence, using the SEA configuration of motors, pulleys, springs, cables, and a torque sensor, e.g., current sensor, the slippage scenarios can be simply detected and potentially prevented, without using the force-sensitive resistor (FSR) sensors, making the fingertip design less complex and decreasing the overall price.

Despite some papers suggesting the external disturbance estimation using SEA configuration of motor and spring [23], to the best of our knowledge, this is the first time that the slippage detection is addressed in the prosthetic hands using the SEA concept and without using FSR sensors.

6) Safe interaction: Humans interact with the environment mostly with their hands; thus, the hand faces lots of external disturbances, impacts, and forces. In biology, the compliant joints and soft tissues are responsible for minimizing external disturbances and damages [27]. Using a similar analogy, in prosthetic hands actuated by SEA, the external forces are transferred to the remaining tissues through the spring, which behaves as a low-pass filter and smooths the external disturbances and impacts. Accordingly, safe interaction and shock absorption are important features of prosthetic hands actuated by SEA. Although, SEA may not reflect its inherent safety feature in the short-term, it provides a huge benefit in the long-term usage. A compliant prosthetic hand can prevent/minimize many possible side effects of using rigid prosthetic hands in the long-term; e.g., elbow joint dislocation, tissue damage, and muscle-bone infection.

7) Efficient grasp: To hold an object, the prosthetic hand should continuously apply force. In a prosthetic hand actuated by SEA, unlike rigid prosthetic hands, the applied force can be maintained by halting the motor position and turning the motor off, which can simply done by a brake system. After a while, when the grasp is secured and the motors' torque sensors detect no slippage condition, the hand can go to the power saving mode by the motor's shaft brake activation. This feature drastically minimizes the energy consumption in long-term grasps, but at the same time, the slippage detection feature is disabled.

Without this feature, the user has to fully focus on the muscle activation levels to secure the grasp, which in long-term leads to muscle fatigue, discomfort, and a high level of cognitive load and distraction. However, a combination of SEA and brake-equipped motors enables us with both energy efficiency and comfort; i.e., efficient grasp.

III. EXPERIMENTS AND RESULTS

A comprehensive set of experiments were conducted to evaluate the prosthetic hand's performance. The experimental results are also presented in the uploaded Video File.

A. Position control

Position/posture control is one of the main features of the designed prosthetic hand in free grasp condition. In this experiment, the extensor motor position is increased to show the coordinated finger motions from the fully flexed to the fully extended configurations. The experimental results are presented in Fig.3 A-E. As it can be seen, the hand can be controlled in its course of the motion in five different configurations. Although the resolution of the finger motions is sufficient ($18deg$) for grasping objects with different shapes and diameters, comparing this resolution with the motor encoder resolution ($0.3deg$) indicates that, the hand's motion resolution is highly limited due to setup friction; i.e., the friction at the joints and the friction between the cables and the body.

B. Morphological grasp

To show the capability of the designed prosthetic hand to grasp objects with different shapes, we designed a simple experiment in which the flexor motor position is controlled on a fixed position for different objects. Several objects with

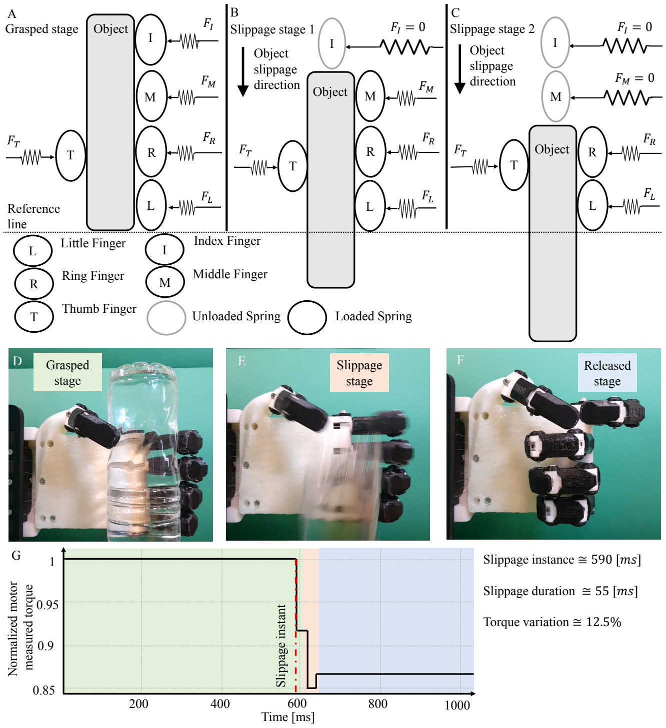

Fig. 5: **The schematic and the experimental results for slippage detection.** (A-C) show a conceptual diagram of the slippage detection algorithm. As it can be seen, the release of each finger yields an instant variation in the motor's measured torque. Using a high-resolution current sensor, the slippage could be detected in the early stages. In low-resolution cases, the slippage is detected when at least one of the fingers is released; see (B). (D-F) show an experimental result in which slippage is detected by observing the variations in the motor's measured torque. These figures start with a (D) grasp condition, followed by a (E) slippage condition, and end with a (F) released condition. (G) also shows the variations of motor estimated torque during the experiment (D-F).

a diverse variety of shapes are considered for this experiment and three of them are illustrated in Fig.4 A-C. Based on the presented results, the designed prosthetic hand can grasp the objects based on their shape. This interesting performance is achieved by a simple position control in the flexor motor, which demonstrates the realization of morphological computation in this design.

C. Force control

In this experiment, a simple folded paper is targeted to grasp, where the applied force after the grasp is controlled in three different conditions: low-force, mid-force, and high-force. The experimental results are illustrated in Fig.3 F-H. As can be seen in the results, the-low force, mid-force, and high-force grasp lead to slippage condition, proper grasp, and crumpled paper, respectively. It is important to note that this result is achieved solely by position control after the grasp without any force sensor. In fact, the applied force can be indirectly controlled by knowing the springs' coefficient and their length and controlling the motor's position accordingly.

D. Impedance control

In robotics, impedance control is a concept for disturbance rejection. Accordingly, an experiment is conducted to evaluate if the designed prosthetic hand can control the hand impedance during the grasp. In this experiment, a bottle of water is released from a fixed position compared to the prosthetic hand in three different conditions: low-impedance, mid-impedance, and high-impedance. The experimental results, depicted in Fig.3 I-L, show the hand configuration in four different conditions: Fig.3 I, an instance before the bottle hit the hand; Fig.3 J, an instance after the bottle hit the hand with low impedance; Fig.3 K, an instance after the bottle hit the hand with mid impedance; and Fig.3 L, an instance after the bottle hit the hand with high impedance.

The experiment was repeated fifteen times. To evaluate the results, we compared the variation of the fingertip markers after the impact in three different cases: low-impedance, mid-impedance, and high-impedance. Compared to low-impedance, mid-impedance leads to 20% lower hand motions after the external disturbance. And compared to low-impedance, high-impedance leads to 50% lower hand motions after the external disturbance. The results effectively show impedance control feature, where the high-impedance condition is twice stiffer than the low-impedance.

E. Slippage detection

Slippage can be observed and detected by variations in the motor torque while holding a fixed position. In many motors, the applied torque is measured by the motor's current sensor, which is a practical solution for slippage detection. Unfortunately, our selected motor was equipped with a load cell with a drastically low resolution, which could not properly detect the object slippage in its very early stage. But, in cases where one of the fingers is released, the motor's load cell could simply detect the slippage.

To test the slippage detection property of the designed setup, an experiment was conducted. In this experiment, the object is forced to be released from the prosthetic hand, and the variations in the motor's load cell are examined. The procedure is repeated thirty times, and according to the results, the slippage could not be detected at its early stages, but once the first finger is released, the slippage could be detected due to a sudden drop in the load cell's measured force. The experiment procedure is illustrated in Fig.5 D-F.

F. Energy efficiency

The utilized motor in our experiments is not equipped with a brake system, but we conducted an experiment to measure the benefits of having SEA with a brake system. We measured the whole setup current in no load (the setup is on, but the motors apply no torque) and loaded (grasp) conditions as $220mA$ and $790mA$, respectively, at $12V$. Hence, it is concluded that having a brake system to unload motors at grasp conditions can compensate $6.85W$ power on average during the grasp of different objects. To understand the importance of this value, consider the Bebionic hand $1.3AH$ battery at $7.5V$. $6.85W$ power compensation would be equivalent to $85min$ operating time per charge.

IV. DISCUSSION AND CONCLUSION

In this paper, we present the advantages of using SEA in the design of an affordable, simple-controlled, and functional prosthetic hand including position control, morphological grasp, force control, impedance control, slippage detection, safe interaction, and efficient grasp. Also, a vast variety of experiments were conducted to evaluate the performance of the designed prosthetic hand. The experimental results demonstrate the effectiveness of SEA to attain the aforementioned features in practice.

Selecting a proper motor with a current sensor and brake is essential to attain some of the mentioned features; i.e., slippage detection, force control, and efficient grasp. In addition, the experiments show that friction is an important factor that can reduce the resolution position control. Also, to have impedance control a pair of motors in an antagonistic configuration is required. By removing this feature, the whole prosthetic hand can be controlled by one motor, and the overall price can be further reduced.

The proposed prosthetic hand requires only two EMG sensors to attain all the mentioned features, hence experimenting the prosthetic hand with a myoelectric interface is our future work, in which we should instruct a wearable prosthetic hand. Another interesting research topic that will be addressed in our future work is adding vibrotactile biofeedback to evaluate if it can help the amputee individuals to properly perceive, react, and prevent the slippage. Another future work would be making the thumb adjustable joint active and the usage of nonlinear springs and pulleys to improve the morphological grasp efficacy.

V. ACKNOWLEDGMENT

Authors would like to thank the University of Tehran for providing support for this research. Authors also thank Mostafa Hamidifard for his comments on the first draft of this paper.

REFERENCES

[1] K. Ziegler-Graham, E. J. MacKenzie, P. L. Ephraim, T. G. Travison, and R. Brookmeyer, “Estimating the prevalence of limb loss in the united states: 2005 to 2050,” *Archives of physical medicine and rehabilitation*, vol. 89, no. 3, pp. 422–429, 2008.

[2] H. Burger, T. Maver, and Č. Marinček, “Partial hand amputation and work,” *Disability and rehabilitation*, vol. 29, no. 17, pp. 1317–1321, 2007.

[3] Y. Hattori, K. Doi, K. Ikeda, and E. P. Estrella, “A retrospective study of functional outcomes after successful replantation versus amputation closure for single fingertip amputations,” *The Journal of hand surgery*, vol. 31, no. 5, pp. 811–818, 2006.

[4] V. Mendez, F. Iberite, S. Shokur, and S. Micera, “Current solutions and future trends for robotic prosthetic hands,” *Annual Review of Control, Robotics, and Autonomous Systems*, vol. 4, pp. 595–627, 2021.

[5] C. Medynski and B. Rattray, “Bebionic prosthetic design.” Myoelectric Symposium, 2011.

[6] W. Guo, W. Xu, Y. Zhao, X. Shi, X. Sheng, and X. Zhu, “Towards human-in-the-loop shared control for upper-limb prostheses: A systematic analysis of state-of-the-art technologies,” *IEEE Transactions on Medical Robotics and Bionics*, 2023.

[7] “Machinery involved in 58 percent of work-related amputations in 2018,” 2020, accessed: 2023-04-12. [Online]. Available: https://www.bls.gov/opub/ted/2020/machinery-involved-in-58-percent-of-work-related-amputations-in-2018.htm

[8] D. Farina, N. Jiang, H. Rehbaum, A. Holobar, B. Graimann, H. Dietl, and O. C. Aszmann, “The extraction of neural information from the surface emg for the control of upper-limb prostheses: emerging avenues and challenges,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 22, no. 4, pp. 797–809, 2014.

[9] M. Boyer, L. Bouyer, J.-S. Roy, and A. Campeau-Lecours, “Reducing noise, artifacts and interference in single-channel emg signals: A review,” *Sensors*, vol. 23, no. 6, p. 2927, 2023.

[10] L. C. Smail, C. Neal, C. Wilkins, and T. L. Packham, “Comfort and function remain key factors in upper limb prosthetic abandonment: findings of a scoping review,” *Disability and rehabilitation: Assistive technology*, vol. 16, no. 8, pp. 821–830, 2021.

[11] Z. Chen, H. Min, D. Wang, Z. Xia, F. Sun, and B. Fang, “A review of myoelectric control for prosthetic hand manipulation,” *Biomimetics*, vol. 8, no. 3, p. 328, 2023.

[12] R. Nasiri, M. Rayati, and M. N. Ahmadabadi, “Feedback from monoarticular muscles is sufficient for exoskeleton torque adaptation,” *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, vol. 27, no. 10, pp. 2097–2106, 2019.

[13] H. Aftabi, R. Nasiri, and M. N. Ahmadabadi, “Simulation-based biomechanical assessment of unpowered exoskeletons for running,” *Scientific Reports*, vol. 11, no. 1, p. 11846, 2021.

[14] R. Nasiri, H. Aftabi, and M. N. Ahmadabadi, “Human-in-the-loop weight compensation in upper limb wearable robots towards total muscles’ effort minimization,” *IEEE Robotics and Automation Letters*, vol. 7, no. 2, pp. 3273–3278, 2022.

[15] P. Sattari, D. Ravanshid, and R. Nasiri, “Designing for practicality: A personalized and adaptive framework for real-time emg-based hand motor decoding,” *TechRxiv*, pp. 1–11, 2024.

[16] M. G. Catalano, G. Grioli, E. Farnioli, A. Serio, C. Piazza, and A. Bicchi, “Adaptive synergies for the design and control of the pisa/iit softhand,” *The International Journal of Robotics Research*, vol. 33, no. 5, pp. 768–782, 2014.

[17] W. Chen, C. Xiong, and S. Yue, “Mechanical implementation of kinematic synergy for continual grasping generation of anthropomorphic hand,” *IEEE/ASME Transactions on mechatronics*, vol. 20, no. 3, pp. 1249–1263, 2014.

[18] B. Vanderborght, A. Albu-Schäffer, A. Bicchi, E. Burdet, D. G. Caldwell, R. Carloni, M. Catalano, O. Eiberger, W. Friedl, G. Ganesh *et al.*, “Variable impedance actuators: A review,” *Robotics and autonomous systems*, vol. 61, no. 12, pp. 1601–1614, 2013.

[19] H. Hua, Z. Liao, and J. Zhao, “Design, analysis, and experiment of an underactuated robotic gripper actuated by linear series elastic actuator,” *Journal of Mechanisms and Robotics*, vol. 15, no. 2, p. 021002, 2023.

[20] B. Laschowski and J. McPhee, “Energy-efficient actuator design principles for robotic leg prostheses and exoskeletons: A review of series elasticity and backdrivability,” *Journal of Computational and Nonlinear Dynamics*, vol. 18, no. 6, p. 060801, 2023.

[21] S. Oh and K. Kong, “High-precision robust force control of a series elastic actuator,” *IEEE/ASME Transactions on mechatronics*, vol. 22, no. 1, pp. 71–80, 2016.

[22] R. A. B. Petrea, R. Oboe, and G. Michieletto, “Safe high stiffness impedance control for series elastic actuators using collocated position feedback,” *IEEJ Journal of Industry Applications*, vol. 12, no. 4, pp. 735–744, 2023.

[23] M. Yokoyama, R. A. B. Petrea, R. Oboe, and T. Shimono, “External force estimation in linear series elastic actuator without load-side encoder,” *IEEE Transactions on Industrial Electronics*, vol. 68, no. 1, pp. 861–870, 2020.

[24] R. Ham, T. Sugar, B. Vanderborght, K. Hollander, and D. Lefeber, “Compliant actuator designs,” *IEEE Robotics & Automation Magazine*, vol. 3, no. 16, pp. 81–94, 2009.

[25] J. Fajardo, V. Ferman, D. Cardona, G. Maldonado, A. Lemus, and E. Rohmer, “Galileo hand: An anthropomorphic and affordable upper-limb prosthesis,” *IEEE access*, vol. 8, pp. 81 365–81 377, 2020.

[26] V. C. Müller and M. Hoffmann, “What is morphological computation? on how the body contributes to cognition and control,” *Artificial life*, vol. 23, no. 1, pp. 1–24, 2017.

[27] Y. Nakanishi, T. Izawa, T. Kurotobi, J. Urata, K. Okada, and M. Inaba, “Achievement of complex contact motion with environments by musculoskeletal humanoid using humanlike shock absorption strategy,” in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, 2012, pp. 1815–1820.