Average Power as an Alternative Variable for Power Grip Control in Robotic Hands Without Using Force Measurements

Juan F. Solarte, and Carlos A. Gaviria

Abstract—**Power grip is one of the fundamental functionalities of a robotic hand prosthesis, as it is essential for performing various activities of daily living. This study proposes the use of the average electrical power consumed by the actuators as a variable correlated with grip force in mechanisms with an effective degree of freedom equal to one. This approach enables the implementation of closed-loop grip force control schemes without the need for force sensors. To evaluate the performance of the proposed method, a five-finger underactuated robotic hand prototype was developed, along with a cascade control scheme to track an average power reference. The system was implemented in the Simulink environment of Matlab, using an Arduino Mega 2560 board for signal acquisition and actuator control. The power–force relationship was validated using a variable stiffness device, in accordance with recommendations from a standardized protocol for evaluating the quality of robotic hand prostheses. The results show that average electrical power exhibits a stronger correlation with grip force than electric current, which has been used for similar purposes in previous studies. This work addresses the challenge of controlling grip force without force sensors, introducing a variable that has not been previously exploited for this purpose.**

Link to graphical and video abstracts, and to code: https://latamt.ieeer9.org/index.php/transactions/article/view/9871

Index Terms— **Current; Energy efficiency; Grasping; PID control; Prosthetic hand; Sensorless control**

I. Introduction

THE development of robotic hand prostheses has advanced significantly in recent years, with the aim of replicating both the functionality and dexterity of the human hand. One of the primary functions of these prostheses is Power grip, which enables the user to hold an object through the force generated by the opposition between the finger phalanges and the palm[1]-[7]. This capability allows users to securely grasp and manipulate objects, making it crucial for performing daily activities such as lifting weights, holding tools, or executing movements that require firmness and stability [8]-[11].

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In Colombia, decades of armed conflict have resulted in thousands of civilian casualties caused by landmines and explosive remnants of war. As of March 2025, more than 12,500 individuals have been affected, many of whom have suffered upper-limb amputations, including traumatic hand loss [12]. In this context, there is a clear and pressing need to develop prosthetic hand solutions that are functional, affordable, and adapted to the needs and conditions of those affected by the conflict.

Grip force refers to the amount of force a prosthesis can exert when grasping or holding an object. It is a key parameter of functional performance, as it determines the prosthesis's ability to carry out daily tasks effectively and safely. The amount of force transmitted to the object being grasped depends on the mechanical system that conveys force from the actuators to the object, the object's shape and size, and the friction between the fingers and the object [13]. Consequently, it is not straightforward to predict the exact value of the required force in a specific grasp configuration.

To achieve Power grip functionality, several authors have proposed various strategies for regulating grip force, with notable approaches including compliance control, hybrid control, and impedance control.

Compliance control enables the hand to adjust its stiffness during interaction with objects, facilitating adaptation to different shapes, textures, and fragilities[14], [15]. Hybrid position/force control allows the hand to move to specific locations while simultaneously applying a defined force, alternating between control modes [13], [16], [17]. Impedance control is particularly common in power grip tasks, enabling the system to grasp both delicate and heavy objects by adjusting impedance [18], [19]-[22].

In control strategies that require force references, a key challenge is obtaining accurate grip force measurements. This necessitates that the prosthesis be equipped with exteroceptive sensors capable of capturing grip force data [23]. For this reason, several authors have developed control schemes in which feedback relies on force sensors located at the fingertips, using Force Sensitive Resistors (FSRs) [11], [24]-[30] or load cells [31]. For validation purposes, force sensors are often embedded within test objects such as cylinders or spheres [11],[32]-[37].

Some studies on robotic manipulators assess grip force by measuring it at the end-effector, analyzing its relationship with motor current [38]. In robotic hand force control, a widely adopted strategy is the cascade control scheme, typically combining an inner loop and an outer loop with different control objectives. Reported configurations include: inner current control with outer PID-based torque control [16]; current inner loop with outer compliance control [39]; outer impedance control with inner current regulation [33], [40], and force-position loop combinations leveraging joint kinematics[41].

Several authors have explored controlling grip force without force sensors, using actuator current due to its relation with generated torque. However, our review of the literature reveals two key limitations: (i) Current is highly sensitive to high-frequency electrical noise, yet most studies do not report how this is managed; (ii) The relationship between actuator current and actual grip force has not been systematically studied.

This work proposes the use of average electrical power consumed by the actuators as an alternative variable correlated with grip force. To the best of our knowledge, no prior studies have established or validated a relationship between average power and grip force in robotic hand prostheses.

As an averaged quantity, average power inherently filters high-frequency noise introduced by switching electronics. This is advantageous for real-time control, particularly in prosthetic applications.

Furthermore, the approach is supported by biological inspiration: in human power grips, force is related to the muscular power generated during contraction, often estimated using electromyographic signals.

Based on these insights, we hypothesize that average electrical power is more closely related to grip force than current, and that it can be used as a controlled variable in force regulation strategies—without the need for force sensors.

To test this hypothesis, a five-finger underactuated robotic hand prototype was developed, featuring fingers with a single effective degree of freedom. A cascade control strategy was implemented to track average power references. The power–force relationship was experimentally validated using a variable-stiffness cylindrical object following the evaluation protocol proposed by NIST [42].

The results demonstrate that average power is more strongly correlated with grip force than current, and confirm the feasibility of using it as a feedback variable in grip force control schemes—eliminating the need for direct force measurement and reducing the complexity, cost, and maintenance requirements of the system.

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II. Materials and Methods

This section describes the design of the robotic hand prosthesis, the measurement system developed to estimate grip force, the implemented hardware/software experimental setup, the cascade force control scheme, and the computation of average power.

A. Hand Design

The hand design used in this work is based on the model presented in [43], which implements a six-bar linkage mechanism for the index, middle, ring, and little fingers. All four fingers share an identical structure but are positioned differently around the palm. Their identical geometry facilitates design, manufacturing, and interchangeability of components. The thumb employs a four-bar linkage mechanism, but its design remains similar to the other fingers. Each finger has one effective degree of freedom and is actuated individually: the index, middle, and ring fingers use Actuonix L12p linear actuators[44], while the thumb is driven by an Actuonix PQ12p actuator [45]. The little finger is mechanically coupled to the ring finger, so both are controlled by a single actuator. In total, the hand comprises five fingers and four actuators. The CAD model was created using SolidWorks, and the components were fabricated with a 3D printer using PLA and ABS materials (see Fig. 1).

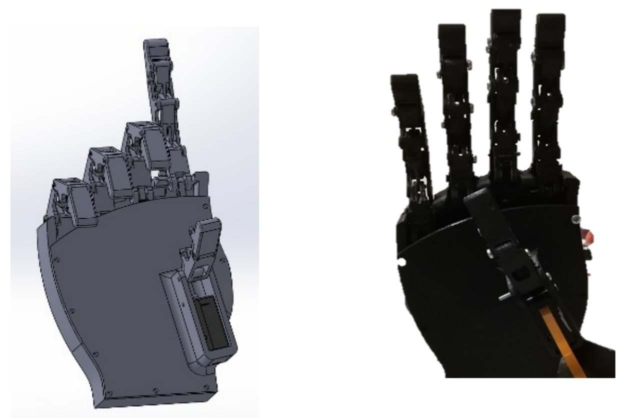

Fig. 1. CAD model and hand assembly.

The mechanism that transmits the flexion and extension motion to the fingers is illustrated in Fig. 2. It consists of a linear actuator coupled to the finger linkage mechanism through a sliding element.

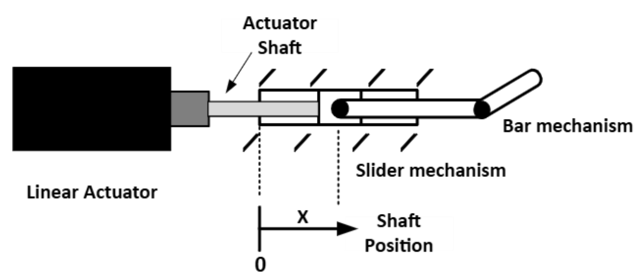

Fig. 2. Finger motion mechanism.

The number of effective degrees of freedom of the mechanism, denoted as ne, for the index finger—and similarly for the thumb—is defined as $ne = n - r$, where n is the number of joints and r is the number of constraints in closed-chain mechanisms. It is assumed that the number of active joints na must equal the number of effective degrees of freedom, i.e., $na = n - r$. Given that the number of passive joints is $np = n - na$, it follows that $np = r$. For the six-bar linkage mechanism of the index finger, $n = 8$, $np = 7$, and the effective number of degrees of freedom is $ne = 8 - 7 = 1$.

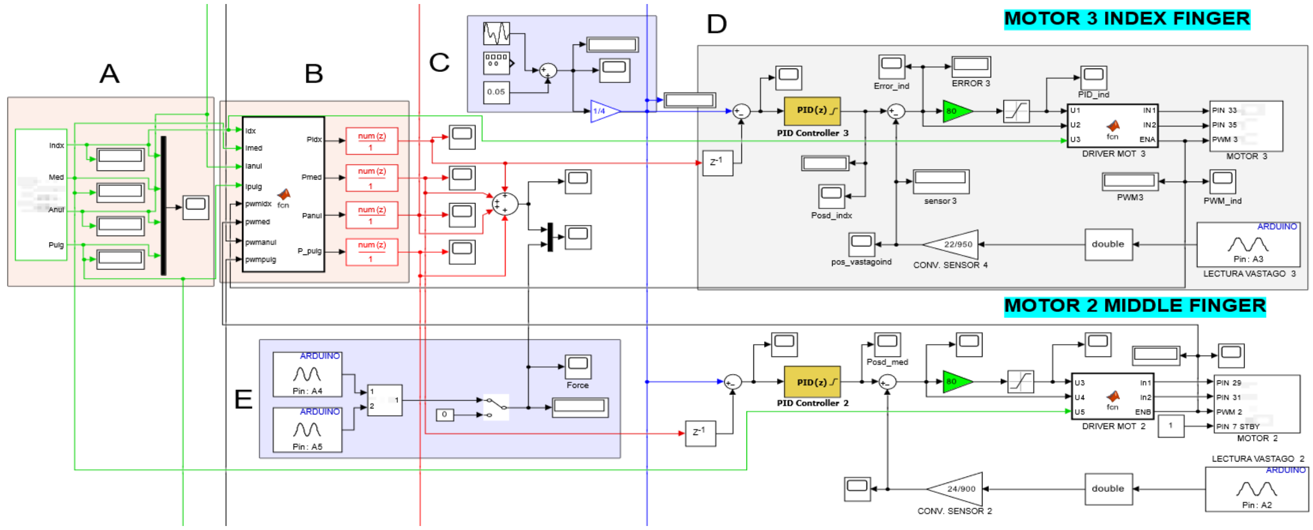

Fig. 4. Block diagram for the index and middle fingers using the Simulink Support Package for Arduino Hardware. (A) Current sensing stage, (B) Average power calculation, (C) Reference signal generation, (D) Cascade control loop, (E) Force measurement.

The same result can be obtained for the thumb, and it implies that, when considering the fingertip as the end-effector, its position and the force it exerts are uniquely related to the position and force applied at the active joint.

B. Grip Force Measurement

Following the performance metrics and test methods for robotic hands defined in [42], a variable-stiffness cylinder was designed and 3D printed to measure the grip force exerted by the robotic hand. This cylinder was internally equipped with a pair of springs and force-sensitive resistors (FSRs) [46], to capture force values exerted by the hand as the springs were compressed (see Fig. 3). This configuration enables safe application of grip forces over a continuous range, without compromising the integrity of the hand mechanisms. The measurement procedure involved alternating between closing and opening postures while recording force data. The FSR sensor readings were previously calibrated using known weights within the sensors' dynamic range, and a polynomial curve was fitted to the measurements using least squares regression. Grip force was computed as the sum of the forces recorded by both sensors. Fig. 3 shows the robotic hand performing a Power grip on the cylinder by varying the position references of the finger actuators.

C. Experimental Setup

The control system was implemented using the Simulink Support Package for Arduino Hardware and executed on an Arduino Mega 2560 board in *external mode* [47] , which allows Simulink to interact with the board, acquire sensor data, and send control signals to the actuators in real time (See Fig. 4). A custom electronic board was designed and fabricated as a shield for the Arduino 2560. TB6612FNG motor drivers [48] were used to control the actuators, and INA219 current sensors [49] were used to measure actuator current (See Fig.5). The linear actuators are equipped with internal potentiometers, which provide the actuator shaft position as a measurable voltage.

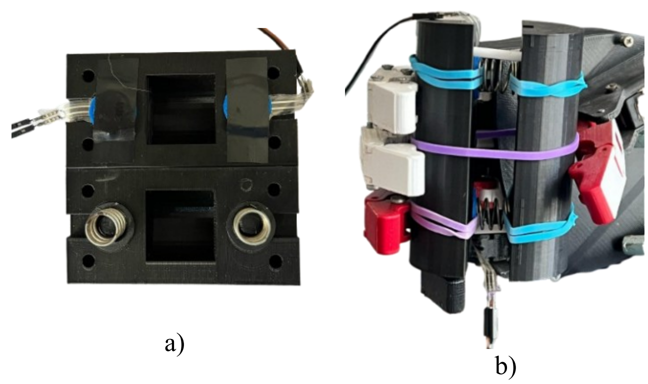

Fig. 3. Experimental setup with the variable-stiffness cylinder: a) Internal view of the cylinder showing the embedded spring mechanism used to simulate variable stiffness, b) Power grip performed by the prosthetic hand on the modified cylinder.

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D. Average Power Calculation

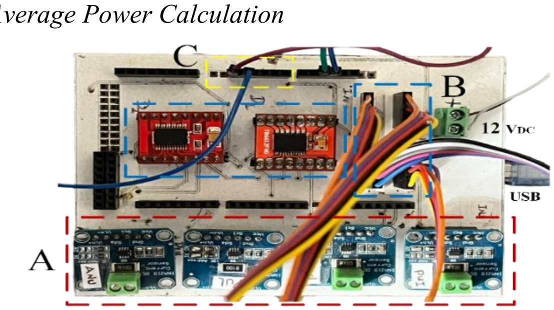

Fig. 5. Custom shield for Arduino Mega 2560: a) INA219 current sensors, b) TB6612FNG motor drivers with output connectors, c) ADC inputs for two analog channels.

The control approach proposed in this work is based on the relationship between the force exerted on an object by the hand and the average power applied to an actuator in an underactuated robotic mechanism used in a hand prosthesis. This relationship is supported by a biologically inspired foundation. It has been shown that there is a correlation between the root mean square (RMS) of a surface electromyography (sEMG) signal and the muscle force exerted [50].This operation is typically performed using a moving analysis window, which acts as a filter on the original signal and captures the electrical activity of the muscles in relation to muscle power.

The average power applied to the actuator driving the underactuated mechanisms responsible for finger motion in the robotic hand prosthesis is expected to exhibit a proportional relationship with the force applied to the object, provided that the actuation mechanism has a single effective degree of freedom. In the case considered in this study, each finger mechanism is based on linkage structures, where motion is transmitted via a bar driven by a linear actuator powered by a direct current (DC) motor. It is assumed that the motor armature current can be measured and that the armature voltage—applied through a PWM signal governed by the control law—can also be known at each sampling instant. The average power delivered to the motor at a given sample k can be calculated using a rectangular moving window of N samples, as expressed in Equation (1).

$$P_{av}[k] = \frac{1}{N}\sum_{k=n-N+1}^{n} i[k]v[k] \qquad (1)$$

where $i[k]$ is the current consumed by the actuator at discrete time k,and $v[k]$ is the voltage applied to the actuator at time k.

This calculation can be implemented using a rectangular moving window FIR averaging filter. However, such a filter introduces a delay of $N/2$ samples, and the rectangular window also presents disadvantages such as edge effects. A similar performance can be achieved using an exponential filter, which is more suitable for real-time applications, as it requires only two operations per sample, despite its nonlinear phase response. Equation (2) defines the exponential filter, where α is a parameter in the range (0,1) that is adjusted to achieve an appropriate trade-off between smoothness and delay.

$$P_{av}[k] = \alpha\, i[k]v[k] + (1-\alpha)P_{av}[k-1] \qquad (2)$$

With a small α value (close to 0), the filter assigns more weight to past values and less to the current input, resulting in a smoother but slower signal. Conversely, a large α value (close to 1) yields faster responses but provides less smoothing. In this work, the tuning criterion for the α parameter was to achieve a zero-lag response in the cross-correlation curve between the measured grip force and the computed average power variable, as will be detailed in the results section.

The filter in Equation (2) is applied identically to all four actuated fingers, and the total average power is computed as the sum of the average power contributions from each individual finger.

E. Power Control Scheme

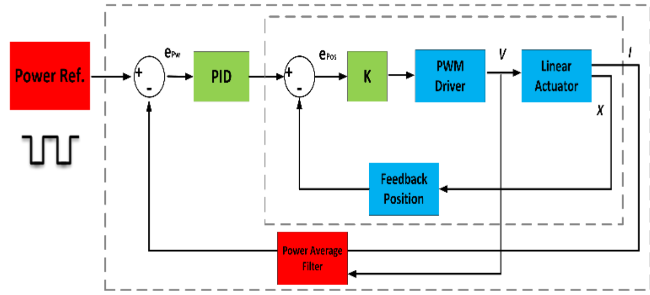

Fig. 6. Grip force control loop for a single finger.

Several control strategies used for grip force regulation in robotic hand prostheses adopt a cascade configuration, with either a current inner loop or a position inner loop, depending on the control variable. The scheme proposed in [16] follows this structure. The control architecture shown in Fig. 6 consists of an inner loop using proportional control and an outer loop employing a discrete-time PID controller. The entire control loop is implemented in Simulink, and the PWM output signals are sent to the linear actuators. This scheme is identical for all four actuated fingers of the robotic hand.

Controller tuning was carried out without model estimation, using the standard empirical procedure: the inner loop gain was first adjusted to achieve fast position reference tracking with minimal steady-state error, and the outer PID controller was tuned using a widely known empirical method. The following section provides the values of the outer loop constants K_p, K_i, and K_d, as well as the inner loop gain K, for each finger.

TABLE I
TUNING VALUES FOR THE EXTERNAL LOOP PID CONSTANTS AND THE INTERNAL LOOP GAIN

Finger	K_p	K_i	K_d	K
Index	-40	0.01	0.1	80
Middle	-40	0.01	0.1	80
Ring	-55	0.01	0.1	80
Thumb	-40	0.01	0.1	80

III. RESULTS

The results obtained demonstrate the effectiveness of the proposed system for controlling grip force in a robotic hand prosthesis using average electrical power as a reference. The most relevant findings are presented below, organized into two key aspects: 1) Correlation between electrical power and applied force, and 2) Performance of the cascade control system.

A. Correlation between Electrical Power and Applied Force

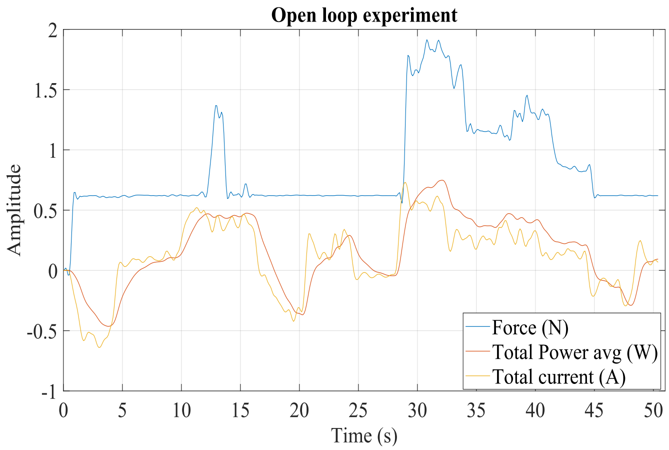

Fig. 7. Grip force, average power, and current during reference tracking.

It can be observed that, although current is commonly used in the literature as a variable correlated with grip force, it is inherently noisy due to the nature of the voltage being applied to the motors via a PWM modulator, which operates at a switching frequency much higher than the mechanical response time of the actuator sliders. To quantify the correlation between total grip force and both total average power and total current, the cross-correlation algorithm in MATLAB was used, employing the *xcorr* function. The results are shown graphically in Figure 8.

Figure 8 clearly demonstrates that the total grip force exhibits a stronger correlation with total average power than with total current. This behavior is also influenced by the application of the exponential filter, which allows a low-latency response between the computation of average power and the measured grip force. Although actuator current has been widely used in previous control strategies for robotic hands, the present results suggest that average power may serve as a more reliable and less noisy control variable in grip force regulation tasks for robotic prostheses.

This observation is further supported through a quantitative comparison using least-squares linear regression models. Two models were fitted to estimate grip force based on current and average power, respectively. The adjusted coefficient of determination R^2, which measures the proportion of variance in the dependent variable explained by the model, was computed for both cases. Figure 9 shows a comparison between the estimated grip force values obtained from each model, after bias removal. The models were implemented using the *fitlm* function in MATLAB and include both intercept and slope parameters from the regression line. The adjusted R^2 coefficients for average power and current were 0.512 and 0.285, respectively, indicating that a linear regression model using average power as the independent variable explains the variability of the estimated grip force more effectively than one based on current.

However, this result also demonstrates that a linear model relating total grip force to average power is not sufficient to fully describe the system's dynamic behavior. This limitation can be attributed to nonlinearities in the gripping process of the cylindrical object, such as dry friction, slippage, or the mechanical behavior of the rigid spring used in the deformable cylinder shown in Figure 3. In particular, the presence of a rigid spring introduces a nonlinear relationship between the magnitude of the average power and the grip force required to achieve a desired grasp.

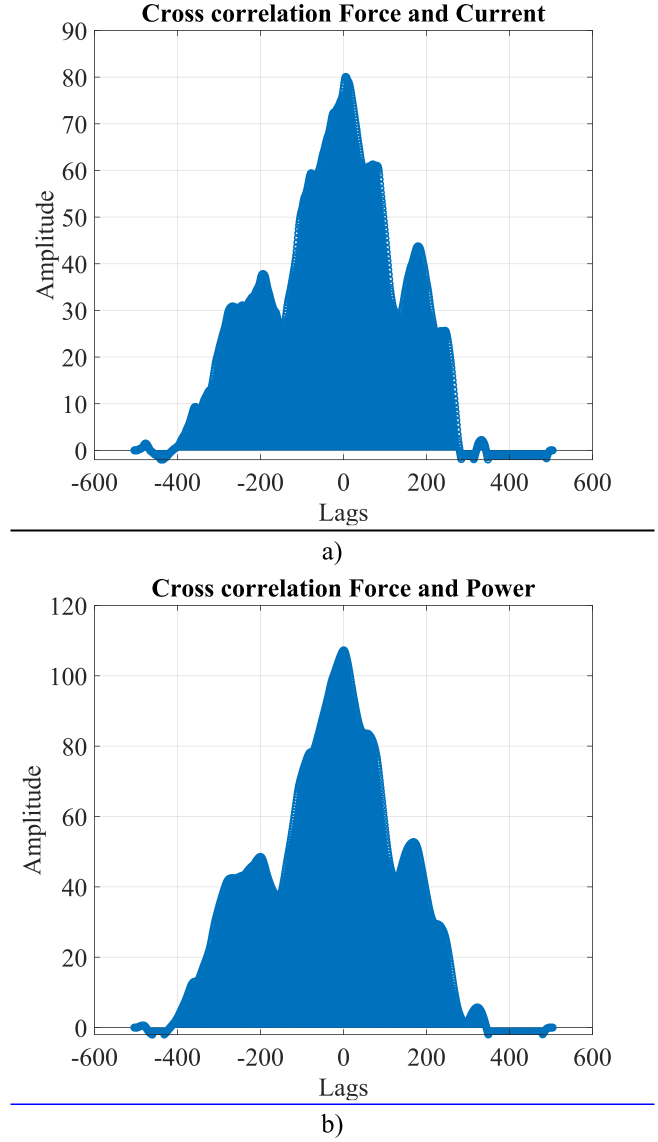

Fig. 8. Cross-correlation between grip force and a) current, b) average power.

Furthermore, in practical applications where the object to be grasped is unknown, the relationship between average power and the applied force will also be unknown and potentially nonlinear, as observed in the experimental setup used in this study. For this reason, the proposed approach does not aim to estimate the applied force directly. Instead, average power is used as the controlled variable, enabling the control strategy to achieve the objective of applying force to an unknown object—an essential and realistic goal in robotic hand prosthesis applications.

B. Performance of the Cascade Control System

To validate the performance of the cascade control scheme described in the methodology section—where the outer loop tracks a total average power reference using a PID controller,

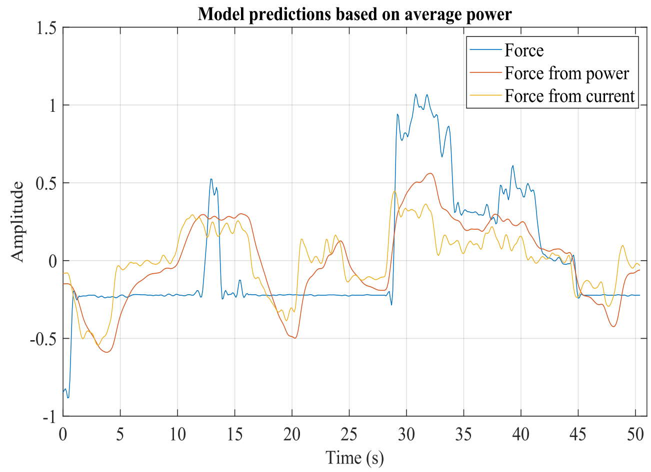

Fig. 9. Grip force estimation using linear regression models.Comparison of Grip Force Estimation Using Linear Regression Models Based on Current and Average Power.

and the inner loop adjusts the actuator shaft position via proportional control—two experiments were conducted. In the first experiment, a periodic reference signal was generated, alternating between zero and a nonzero average power value, as shown in Figure 10. Both the total average power applied to the four actuators and the tracking error with respect to the power reference were recorded. The large initial error is explained by the fact that the hand starts in contact with the object.

For comparison, the total grip force recorded inside the cylinder is also reported. Although its behavior appears somewhat erratic, it should be noted that all five fingers (four active and one passive) contact the cylinder at varying positions due to the relatively smooth contact surfaces and slippage during each change in the applied force. This is further supported by the actuator position data for the active fingers shown in Figure 11, which vary from one period of the power reference signal to another due to changes in the contact points between the hand and the object. Nonetheless, the experiment confirms the feasibility of regulating the overall grip force amplitude through the proposed control strategy, using a power reference alone and without relying on force sensors in the feedback loop.

The second experiment employed a smoother desired average power reference, varying according to a cosine waveform, as illustrated in Figure 12. The tracking error confirms that the control scheme successfully achieves its objective. As in the previous experiment, the large initial error is attributed to the initial adjustment of the fingers to the object.

Figure 13 shows the positions required by the linear actuators of the four active fingers to follow the average power reference, demonstrating that each finger contributes to the overall power grasp.

It is important to note that the focus of this paper is on the control of power grasp. In the literature on robotic hands, object grasping is commonly divided into distinct phases: a pre-shaping phase, in which the fingers are positioned over contact points to ensure a stable grasp, and the grasping phase itself, where contact has already been established and the goal is to apply force to the object through those contact points.

In robotic hand prostheses, achieving both phases involves a trade-off between grasping performance and system practicality, due to significant limitations in available sensors and computational resources. As a result, hybrid control strategies are often implemented, switching between a position control phase, which sets the finger configuration for different types of grasps (e.g., precision, lateral, power), and a force control phase, which applies force once contact is established. This work specifically contributes to the development of the force control phase.

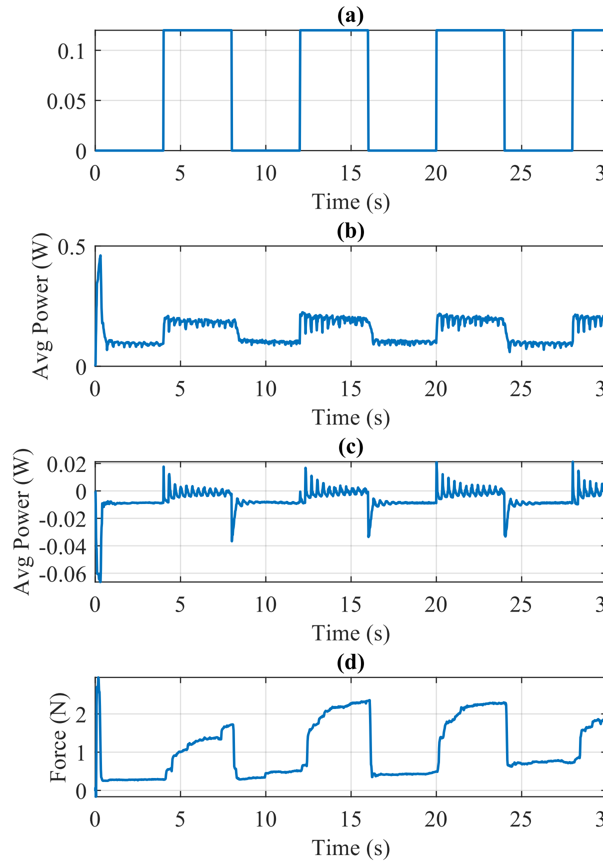

Fig.10. Signals during square waveform reference tracking: a) Square waveform, b) Measured average power, c) Tracking error, d) Measured grip force.

To quantify key attributes of the tracking error in the two previous experiments, the following statistical indicators were computed: root mean square (RMS), mean, and standard deviation (STD). The values obtained for the tracking error of the square setpoint were: $RMS = 1.0 \times 10^{-2}$, $mean = -6.5 \times 10^{-3}$, and $STD = 8.4 \times 10^{-3}$. For the sinusoidal setpoint, the corresponding values were: $RMS = 1.6 \times 10^{-2}$, $mean = -1.3 \times 10^{-2}$, and $STD = 9.2 \times 10^{-3}$.

Based on these indicators, it can be observed that the system exhibits a low RMS value, indicating that the controller achieves accurate tracking of the reference signal in general. The mean error being close to zero suggests the absence of systematic bias. Meanwhile, the standard deviation provides insight into how the signal is affected by disturbances or measurement noise.

It is worth noting that the tracking performance for the square setpoint yields better statistical indicators than for the sinusoidal case, which may be attributed to the characteristics of the PID control strategy. These results confirm the feasibility of the proposed control scheme, which uses total average power as the controlled variable to regulate grip force in a power grasp, without requiring force sensors in the feedback loop.

The main objective of these preliminary results is to demonstrate the viability of using average power as an alternative control variable for the power grasping problem in robotic prosthetic hands. Further research is required to fully exploit the potential of this variable as the basis for robust or model-based control strategies, such as sliding mode control [51] or adaptive control [52], to achieve additional objectives, including slippage compensation.

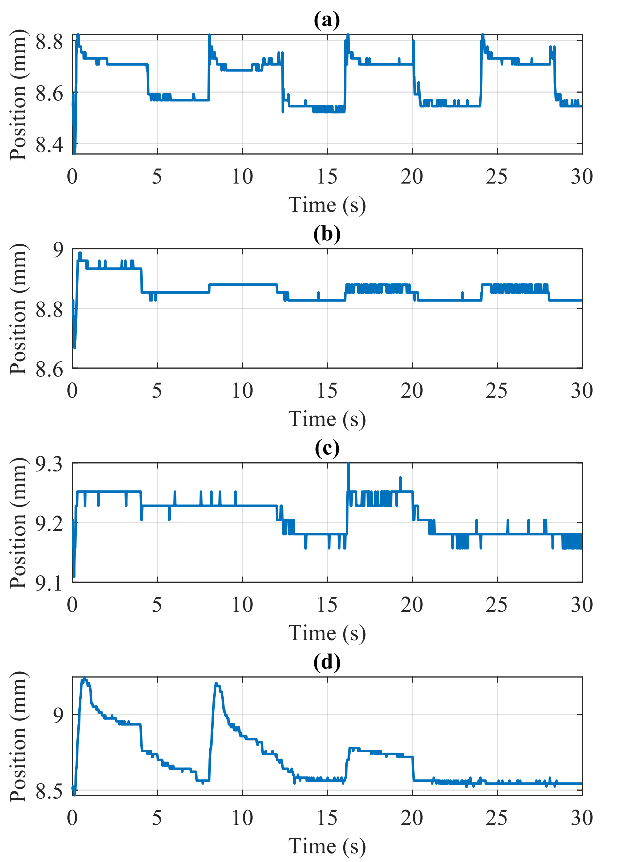

Fig. 11. Actuator shaft positions in response to a square wave average power reference: a) Index finger, b) Middle finger, c) Ring finger, d) Thumb finger.

IV. Conclusions

This work explored the feasibility of using the total average power consumed by the actuators of a robotic hand prototype—whose fingers each have a single effective degree of freedom—as the controlled variable in a grip force control scheme applied to a cylindrical object during a Power grip. The motivation lies in the ability to regulate grip force without requiring direct force measurements. The main contribution to this problem is based on the observation that, although several authors have addressed this challenge by using electric current measurements due to their known relationship with the torque produced by DC motors, none have explicitly studied the correlation between current and the total grip force perceived by the object.

This study demonstrated that total average power exhibits a stronger correlation with grip force than total current. Experimental results show that, by using total average power as the controlled variable, it is possible to effectively regulate the total grip force applied to the object within a closed-loop cascade control scheme. This finding is significant, as it introduces a new measured variable—total average power—that may offer advantages over the electric current variable commonly used in previous works.

The average power computation was implemented using an exponential filter, which is suitable for real-time applications due to its computational simplicity. Its mathematical model could be integrated into model-based control schemes in future research.

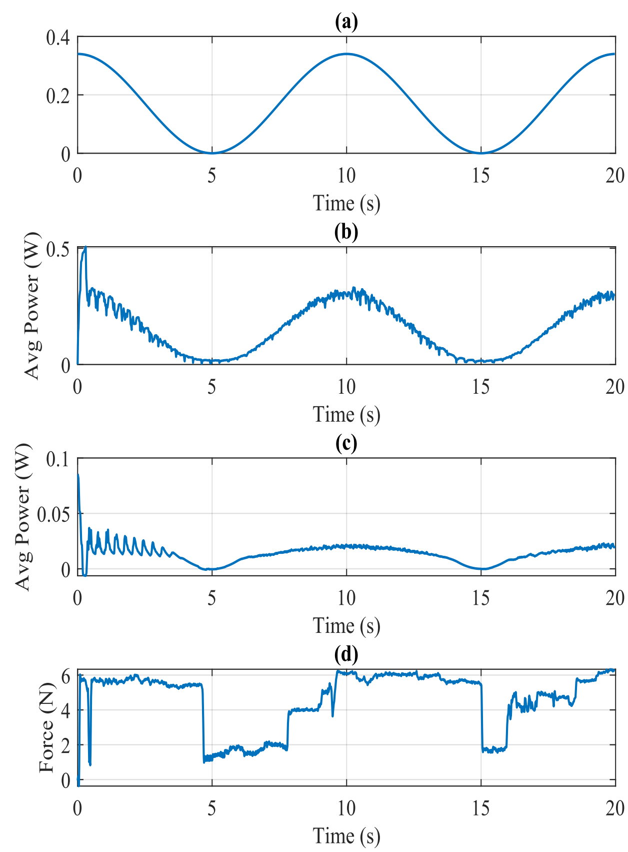

Fig. 12. Signals for cosine waveform average power reference tracking: a).Cosine waveform, b) Measured average power, c) Tracking error, d) Measured grip force.

Acknowledgments

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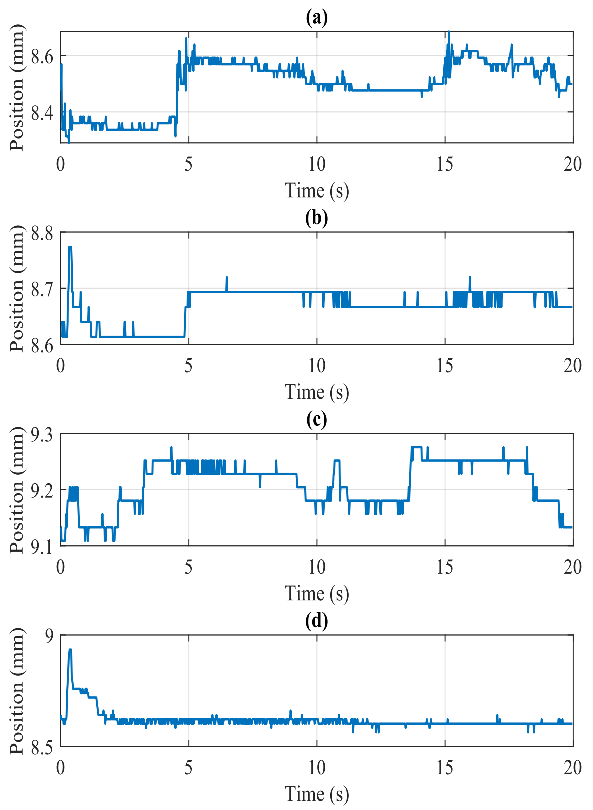

Fig. 13. Actuator shaft positions in response to a cosine waveform average power reference: a) Index finger, b) Middle finger, c) Ring finger, d) Thumb finger.

REFERENCES

[1] M. R. Cutkosky and P. K. Wright, "Modelling Manufacturing Grips and Correlations With the Design of Robotic Hands.," in *Robotics and Automation, Proceedings.*, IEEE, 1986, pp. 1533–1539.

[2] J. Fischer, N. W. Thompson, and J. W. K. Harrison, "The prehensile movements of the human hand," *Classic Papers in Orthopaedics*, vol. 38 B, pp. 343–345, 1956, doi: 10.1007/978-1-4471-5451-8_85.

[3] N. M. Hanafiah, R. Sam, and N. Buniyamin, "Design of an anthropomorphic robotic hand for power grip posture using SolidWorks," *Proceedings - 2014 5th IEEE Control and System Graduate Research Colloquium, ICSGRC 2014*, pp. 31–36, 2014, doi: 10.1109/ICSGRC.2014.6908691.

[4] H. M. C. M. Herath, R. A. R. C. Gopura, and T. D. Lalitharatne, "Prosthetic hand with a linkage finger mechanism for power grasping applications," *2017 IEEE Life Sciences Conference, LSC 2017*, vol. 2018-Janua, pp. 304–307, 2018, doi: 10.1109/LSC.2017.8268203.

[5] Z. Li, Z. Hou, Y. Mao, Y. Shang, and L. Kuta, "The Development of a Two-finger Dexterous Bionic Hand with Three Grasping Patterns-NWAFU Hand," *J Bionic Eng*, vol. 17, pp. 1–14, 2020, doi: 10.1007/s42235-020-0068-6.

[6] L. E. Sánchez-Velasco, M. Arias-Montiel, E. Guzmán-Ramírez, and E. Lugo-González, "A Low-Cost EMG-Controlled Anthropomorphic Robotic Hand for Power and Precision Grasp," *Biocybern Biomed Eng*, vol. 40, no. 1, pp. 221–237, 2020, doi: 10.1016/j.bbe.2019.10.002.

[7] M. Li, "Learning partial power grasp with task-specific contact," *2016 IEEE International Conference on Robotics and Biomimetics, ROBIO 2016*, pp. 337–343, 2016, doi: 10.1109/ROBIO.2016.7866345.

[8] K. Or, M. Tomura, A. Schmitz, S. Funabashi, and S. Sugano, "Position-force combination control with passive flexibility for versatile in-hand manipulation based on posture interpolation," *IEEE International Conference on Intelligent Robots and Systems*, vol. 2016-Novem, pp. 2542–2547, 2016, doi: 10.1109/IROS.2016.7759395.

[9] H. Moeinnia, H. Su, and W. S. Kim, "Novel Grasping Mechanisms of 3D-Printed Prosthetic Hands," *Advanced Intelligent Systems*, vol. 4, no. 11, Nov. 2022, doi: 10.1002/aisy.202200189.

[10] H. Yang *et al.*, "A lightweight prosthetic hand with 19-DOF dexterity and human-level functions," *Nat Commun*, vol. 16, no. 1, p. 955, Dec. 2025, doi: 10.1038/s41467-025-56352-5.

[11] P. Weiner, J. Starke, F. Hundhausen, J. Beil, and T. Asfour, "The KIT Prosthetic Hand: Design and Control," in *IEEE International Conference on Intelligent Robots and Systems*, Madrid, Spain, Oct. 2018, pp. 3328–3334. doi: 10.1109/IROS.2018.8593851.

[12] Presidencia de la República, "Estadísticas de Asistencia Integral a las Víctimas de MAP y MUSE." Accessed: May 11, 2025. [Online]. Available: https://www.accioncontraminas.gov.co/Estadisticas/Paginas/Estadisticas-de-Victimas.aspx

[13] Joseph T. Belte and Aaron M. Dollar, "Performance Characteristics of Anthropomorphic Prosthetic Hands," in *International Conference on Rehabilitation Robotics Rehab Week Zurich*, Switzerland: IEEE, Jul. 2011. doi: 10.1109/ICORR.2011.5975476.

[14] Y. Xu, C. Jiang, and Y. Jie, "Compliance control for grasping with a bionic robot hand," *Proceedings of the 28th Chinese Control and Decision Conference, CCDC 2016*, pp. 5280–5285, 2016, doi: 10.1109/CCDC.2016.7531942.

[15] A. S. Sadun, J. Jalani, J. Abdul Sukor, and F. Jamil, "Force control for a 3-Finger Adaptive Robot Gripper by using PID controller," in *2016 2nd IEEE International Symposium on Robotics and Manufacturing Automation, ROMA 2016*, Ipoh, Malaysia: IEEE, 2017, pp. 1–6. doi: 10.1109/ROMA.2016.7847807.

[16] B. Choukri, "Hybrid control of the triple force/position/speed in one-finger joint remotely actuated," *EEA - Electrotehnica, Electronica, Automatica*, vol. 64, no. 3, pp. 96–106, 2016.

[17] S. Hernandez-mendez and A. Marin-hernandez, "A Switching Position / Force Controller for Two Independent Finger Gripper over ROS," in *2017 International Conference on Electronics, Communications and Computers (CONIELECOMP)*, Cholula, Mexico: IEEE, 2017, pp. 1–6. doi: 10.1109/CONIELECOMP.2017.7891813.

[18] T. Zhang, L. Jiang, and H. Liu, "A novel grasping force control strategy for multi-fingered prosthetic hand," *Journal of Central South University of Technology (English Edition)*, vol. 19, no. 6, pp. 1537–1542, Jun. 2012, doi: 10.1007/s11771-012-1173-4.

[19] H. Luo, X. Duan, and H. Deng, "Sliding mode impedance control of a underactuated prosthetic hand," in *2014 IEEE*

International Conference on Information and Automation (ICIA), Hailar, China: IEEE, Jul. 2014, pp. 726–729. doi: 10.1109/ICInfA.2014.6932747.

[20] X. Xu, H. Deng, Y. Zhang, and N. Yi, "Compliant Grasp Control Method for the Underactuated Prosthetic Hand Based on the Estimation of Grasping Force and Muscle Stiffness with sEMG," *Biomimetics*, vol. 9, no. 11, Nov. 2024, doi: 10.3390/biomimetics9110658.

[21] S. A. Pertuz, C. H. Llanos, and D. M. Munoz, "Development of a Robotic Hand Using Bioinspired Optimization for Mechanical and Control Design: UnB-Hand," *IEEE Access*, vol. 9, pp. 61010–61023, 2021, doi: 10.1109/ACCESS.2021.3073010.

[22] M. Pfanne, M. Chalon, F. Stulp, H. Ritter, and A. Albu-Schäffer, "Object-Level Impedance Control for Dexterous In-Hand Manipulation," *IEEE Robot Autom Lett*, vol. 5, no. 2, pp. 2987–2994, Apr. 2020, doi: 10.1109/LRA.2020.2974702.

[23] M. Aman *et al.*, "Bionic hand as artificial organ: Current status and future perspectives," *Artif Organs*, vol. 43, no. 2, pp. 109–118, 2019, doi: 10.1111/aor.13422.

[24] H. Bayoumi, M. I. Awad, and S. A. Maged, "An Improved Approach for Grasp Force Sensing and Control of Upper Limb Soft Robotic Prosthetics," *Micromachines (Basel)*, vol. 14, no. 3, Mar. 2023, doi: 10.3390/mi14030596.

[25] Y. Wang, Y. Tian, Z. Li, H. She, and Z. Jiang, "Research on Adaptive Grasping with a Prosthetic Hand Based on Perceptual Information on Hardness and Surface Roughness," *Micromachines (Basel)*, vol. 15, no. 6, Jun. 2024, doi: 10.3390/mi15060675.

[26] G. Fonseca, J. Nunes-Pereira, and A. P. Silva, "3D Printed Robotic Hand with Piezoresistive Touch Capability," *Applied Sciences*, vol. 13, no. 14, p. 8002, Jul. 2023, doi: 10.3390/app13148002.

[27] L. N. Rojas-García, C. A. Chávez-Olivares, I. Bonilla-Gutiérrez, M. O. Mendoza-Gutiérrez, and F. Ramírez-Cardona, "Force/position control with bounded actions on a dexterous robotic hand with two-degree-of-freedom fingers," *Biocybern Biomed Eng*, vol. 42, no. 1, pp. 233–246, Jan. 2022, doi: 10.1016/j.bbe.2021.12.006.

[28] V. Mohammadi *et al.*, "Development of a Two-Finger Haptic Robotic Hand with Novel Stiffness Detection and Impedance Control," *Sensors*, vol. 24, no. 8, Apr. 2024, doi: 10.3390/s24082585.

[29] A. Matos *et al.*, "Three-fingered gripper for multiform object grasping with force feedback sensing control," in *2020 IEEE ANDESCON, ANDESCON 2020*, Institute of Electrical and Electronics Engineers Inc., Oct. 2020. doi: 10.1109/ANDESCON50619.2020.9271990.

[30] A. Prakash and S. Sharma, "A low-cost system to control prehension force of a custom-made myoelectric hand prosthesis," *Research on Biomedical Engineering*, no. Muzumdar 2004, 2020, doi: 10.1007/s42600-020-00064-w.

[31] M. Abdeetedal and M. R. Kermani, "Grasp and Stress Analysis of an Underactuated Finger for Proprioceptive Tactile Sensing," *IEEE/ASME Transactions on Mechatronics*, vol. 23, no. 4, pp. 1619–1626, Aug. 2018, doi: 10.1109/TMECH.2018.2844327.

[32] R. A. Romeo, F. Cordelia, A. Davalli, R. Sacchetti, E. Guglielmelli, and L. Zollo, "An instrumented object for studying human grasping," *IEEE International Conference on Rehabilitation Robotics*, pp. 1031–1036, 2017, doi: 10.1109/ICORR.2017.8009385.

[33] D. Esposito *et al.*, "Evaluation of grip force and energy efficiency of the 'federica' hand," *Machines*, vol. 9, no. 2, pp. 1–19, Feb. 2021, doi: 10.3390/machines9020025.

[34] E. Drelich *et al.*, "Force prediction in the cylindrical grip for a model of hand prosthesis," *Sci Rep*, vol. 13, no. 1, Dec. 2023, doi: 10.1038/s41598-023-43600-1.

[35] F. J. Ruiz-Ruiz, J. Ventura, C. Urdiales, and J. M. Gómez-de-Gabriel, "Compliant gripper with force estimation for physical human–robot interaction," *Mech Mach Theory*, vol. 178, Dec. 2022, doi: 10.1016/j.mechmachtheory.2022.105062.

[36] I. Chang, K. M. Lee, and Y. Liu, "Design concept and kinematic analysis of a compliant anatomical palm mechanism for bio-inspired robotic hand design," *Int J Intell Robot Appl*, 2025, doi: 10.1007/s41315-024-00415-1.

[37] A. Mohammadi *et al.*, "A practical 3D-printed soft robotic prosthetic hand with multi-articulating capabilities," *PLoS One*, vol. 15, no. 5, May 2020, doi: 10.1371/journal.pone.0232766.

[38] M. B. Schäfer, J. G. Meiringer, J. Nawratil, L. Worbs, G. A. Giacoppo, and P. P. Pott, "Estimating Gripping Forces During Robot- Assisted Surgery Based on Motor Current," *Current Directions in Biomedical Engineering*, vol. 8, no. 1, pp. 105–108, Jul. 2022, doi: 10.1515/cdbme-2022-0027.

[39] X. Zhang, T. Zhu, I. Yamayoshi, and D. Hong, "A Force Controlled Under Actuated Robotic Hand with Mechanical Intelligence and Proprioceptive Compliant Actuation," in *2018 IEEE-RAS 18th International Conference on Humanoid Robots (Humanoids)*, Beijing, China: IEEE, Nov. 2018, pp. 1–8. doi: 10.1109/HUMANOIDS.2018.8625017.

[40] A. Ajoudani *et al.*, "Exploring teleimpedance and tactile feedback for intuitive control of the pisa/IIT soft hand," *IEEE Trans Haptics*, vol. 7, no. 2, pp. 203–215, 2014, doi: 10.1109/TOH.2014.2309142.

[41] Yi Zhangl, Li Chu, Wendi Zhuo, and Hua Deng, "Grasping Force Control Preventing Excessive Deformation for underactuated Prosthetic Hands," in *2016 IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC)*, Xi'an, China: IEEE, Oct. 2016. doi: 10.1109/IMCEC.2016.7867518.

[42] J. Falco, K. Van Wyk, and E. Messina, "Performance Metrics and Test Methods for Robotic Hands," Oct. 31, 2018. doi: 10.6028/NIST.SP.1227-draft.

[43] N. Dechev, W. L. Cleghorn, and S. Naumann, "Multiple finger, passive adaptive grasp prosthetic hand," *Mech Mach Theory*, vol. 36, no. 10, pp. 1157–1173, 2001, doi: 10.1016/S0094-114X(01)00035-0.

[44] "Actuonix L12-30-100-12-P." Accessed: Mar. 22, 2025. [Online]. Available: https://www.actuonix.com/l12-30-100-12-p

[45] "Actuonix PQ12-63-12-P." Accessed: Mar. 22, 2025. [Online]. Available: https://www.actuonix.com/pq12-63-12-p

[46] "FSR Sensor, Force Sensing Resistor | Interlink Electronics." Accessed: Mar. 22, 2025. [Online]. Available: https://www.interlinkelectronics.com/force-sensing-resistor

[47] "Execute Real-Time Application in Simulink External Mode by Using Step-by-Step Commands." Accessed: Mar. 22, 2025. [Online]. Available: https://la.mathworks.com/help/slrealtime/gs/execute-real-time-application-in-external-mode-with-step-by-step.html

[48] "SparkFun Motor Driver - Dual TB6612FNG." Accessed: Mar. 22, 2025. [Online]. Available:

https://www.sparkfun.com/sparkfun-motor-driver-dual-tb6612fng-1a.html

[49] "Adafruit INA219 Current Sensor Breakout | Adafruit Learning System." Accessed: Mar. 22, 2025. [Online]. Available: https://learn.adafruit.com/adafruit-ina219-current-sensor-breakout/overview

[50] K. Watanabe, M. Kouzaki, M. Ogawa, H. Akima, and T. Moritani, "Relationships between muscle strength and multi-channel surface EMG parameters in eighty-eight elderly," *European Review of Aging and Physical Activity*, vol. 15, no. 1, pp. 1–10, 2018, doi: 10.1186/s11556-018-0192-z.

[51] E. D. Engeberg and S. G. Meek, "Adaptive sliding mode control for prosthetic hands to simultaneously prevent slip and minimize deformation of grasped objects," *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 1, pp. 376–385, 2013, doi: 10.1109/TMECH.2011.2179061.

[52] M. M. Rayguru, M. R. Elara, B. F. Gomez, and B. Ramalingam, "A Time Delay Estimation Based Adaptive Sliding Mode Strategy for Hybrid Impedance Control," *IEEE Access*, vol. 8, pp. 155352–155361, 2020, doi: 10.1109/ACCESS.2020.3019429.

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