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Adaptive Pincer Grasping of Soft Pneumatic Grippers Based on Object Stiffness for Modellable and Controllable Grasping Quality

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Abstract: In this study, adaptive pincer grasping of soft pneumatic grippers (SPGs) is considered, and we propose how the performance of soft pneumatic actuators (SPAs) and the stiffness of grasped objects can be accounted for in modeling and control. The grasping kinetics was analyzed. The connection between grasping quality and SPA performance is discussed. We also devised a subjective definition of grasping quality due to SPA performance. A modeling technique was established, which makes dominant factors of grasping quality due to the SPA performance predictable over the gripper input. Later, a control architecture was developed. This architecture demonstrates how the grasping is implemented. The modeling technique was used to forecast grasping quality due to the SPA performance and its factors. An experiment was conducted to obtain actual results. The predicted and actual results were correspondingly compared. The results show minute deviation, thereby validating the reliability of the grasping. This study clarifies the association between grasping quality and SPA performance and contributes an advancement toward modellable and controllable task-level variables, such as grasping quality, in SPG pincer grasping.

Keywords: soft gripper; pneumatic gripper; pincer grasping; grasping quality; controllable quality



Citation: Sithiwichankit, C.; Chanchaen, R. Adaptive Pincer Grasping of Soft Pneumatic Grippers Based on Object Stiffness for Modellable and Controllable Grasping Quality. *Robotics* **2022**, *11*, 132. <https://doi.org/10.3390/robotics11060132>

Academic Editor: Po-Yen Chen

Received: 11 October 2022

Accepted: 17 November 2022

Published: 21 November 2022



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1. Introduction

The gripper is one of the most common parts of robotic systems [1,2]. The main responsibility of grippers is to conduct grasping as the hands of the systems [3,4]. Grasping essentially leads to physical interaction between the systems and their environment, which is required to make the systems capable of mechanically manipulating objects [5–7]. Nowadays, available grippers can be categorized into a variety of types [8].

Soft robotics, a branch of robotics in which robots are structurally deformable, is currently gaining considerable attention globally [9,10]. This concept has been applied to a new group of grippers, called soft grippers. One of the widespread types of soft grippers is soft pneumatic grippers (SPGs). SPGs basically comprise two or more soft pneumatic actuators (SPAs). The main advantageous feature of SPAs is that their intrinsically flexible structures can provide admirable compliance, making SPGs able to grasp a variety of objects using simple gripper control [11–13]. Meanwhile, a main concern of operating SPAs is that the SPA structures have infinite degree of freedom (DOF) with nonlinear characteristics [14–16]. This concern leads to a significant challenge in the modeling and control of either SPAs or SPG grasping. Countless state variables are theoretically required to determine, examine, and handle the modeling and control.

The abovementioned complication has led the modeling and control of SPAs to become a main category of studies in soft robotics [17]. Suzumori et al. [18] pioneeringly proposed an empirical model of SPAs. Godage et al. [19] presented an analytical model of variable-length SPAs. Polygerinos et al. [20] proposed an analytical model and the feedback control of fiber-reinforced SPAs with rectangular, hemicircular, and circular shapes. Gerboni et al. [21]

demonstrated feedback control using commercial flex sensors of SPAs. Hao et al. [22] developed an analytical model of amphibious SPAs. Wang and Hirai [23] proposed an analytical model of SPAs with parametric identification. Elgeneidy et al. [24] presented empirical models and model-based feedback control of SPAs. Hainsworth et al. [25] proposed analytical and empirical models of multi-material SPAs with their feedback control. Abbasi et al. [26] established an analytical model and feedforward control in the position and force of SPAs. Tian et al. [27] proposed an analytical model of fibrillar adhesive SPAs. Ibrahim et al. [28] presented an analytical model and observer-based feedback control of SPAs. Despite the presence of them, the modeling and control in such works only concerns actuator-level variables, such as bending angle and blocking force.

Previously, grasping quality was introduced to indicate the subjective satisfaction and outcome of grasping [29]. While its exact physical definition is still unclear, it is certainly a task-level variable. Most studies on grasping quality investigate grasping synthesis of mechanical grippers in the aspect of grasping stability [30,31]. In this consideration, the motion and force transformation between the actuator and task space is essential. Some sources also imply that grasping quality correlates with many other factors, such as gripper performance, manipulator motion, and geometrical compatibility [32]. With the comprehensive associations between grasping quality and these factors, grasping quality should be accurately modeled and controlled. Nevertheless, the exact number of factors has never been concluded. While the factors cannot be completely accounted for, the separate effects of each factor on grasping quality still can be examined to continue the approach toward modellable and controllable grasping quality.

A study on grasping quality in SPG grasping is rarely found. The work of Park et al. [33] highlights that the motion and force transformation is necessary in the consideration of grasping quality, and SPA performance is one of the impactful factors on grasping quality in SPG grasping. Studies on the associations between SPA performance and grasping quality should contribute to the development of the modeling and control of grasping quality in SPG grasping. Motion and force variables in existing models of SPAs cannot be simply translated into the task space, mainly due to the constant-curvature condition applied in the modeling process [34–37]. The connection between SPA performance and grasping quality is, hence, currently incomplete.

Adaptive SPG pincer grasping based on object stiffness is presented in this work. In the proposed grasping, SPA performance is considered at both actuator and task levels. The associations between grasping quality and SPA performance in SPG pincer grasping are also clarified here. The major demanding issue in this work is the modeling and control of SPG grasping. The main contribution of this work is advancing the development toward modellable and controllable task-level variables, such as grasping quality, in SPG pincer grasping.

2. Materials and Methods

2.1. Pincer Grasping of SPG

Pincer grasping is plainly a kind of grasping, where grippers squeeze objects with their fingertips. In SPG pincer grasping, the objects are pressed by the ends of SPAs (Figure 1a). The interaction between the SPAs and objects is a mysterious issue that must be clarified to accomplish the transformation of motion and force between the actuator and task space. There are numerous factors in the interaction. To analyze the interaction due to SPA performance, the effects of other factors must be decoupled. The analysis then proceeded under the assumption that the effects of other factors can be ignored. Under this assumption, we proposed that the exerted force of SPAs on a grasped object, denoted by F_O (Figure 1b), equals the withstanding force of the object on the SPAs, denoted by F_S (Figure 1c), as follows:

$$F_S = F_O \quad (1)$$

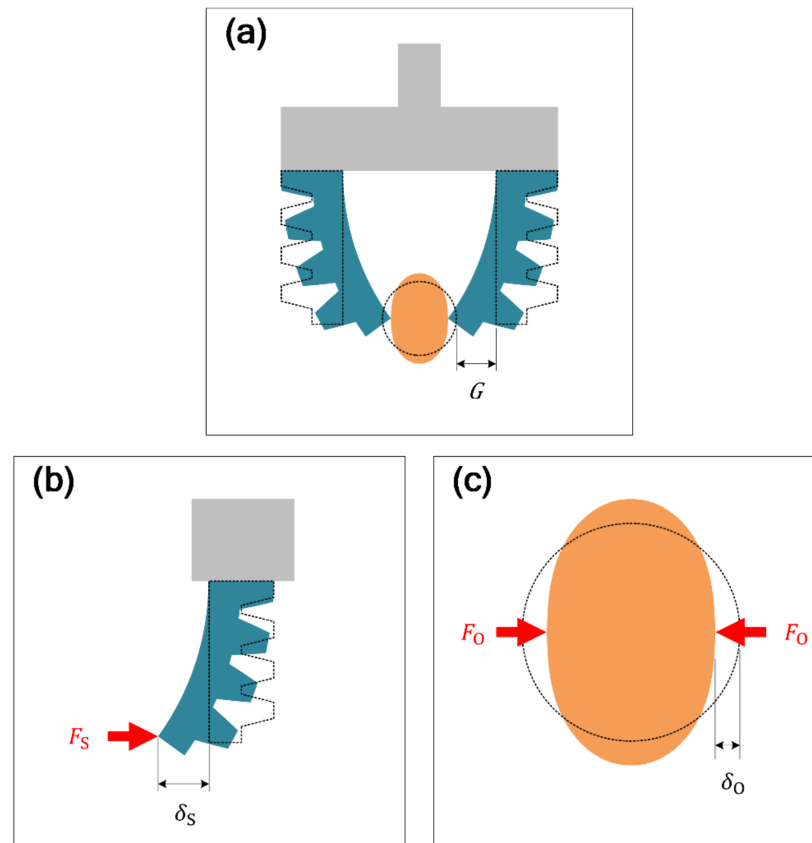


Figure 1. (a) SPG pincer grasping and the gaps between SPAs and a grasped object; (b) deformation and withstanding force on an SPA; (c) deformation and exerted force on a grasped object.

The force transformation is then achievable using Equation (1). According to the geometrical constraint, the deformation of the SPAs, denoted by δ_S (Figure 1b), can be considered equivalent to the summation of the deformation of the objects due to F_O , denoted by δ_O (Figure 1c), and the gap distance between them, denoted by G (Figure 1a), as follows:

$$\delta_S = \delta_O + G, \quad (2)$$

Equation (2) allows us to implement the motion transformation but is applicable only when the SPAs behave similarly throughout grasping. In cases when the SPAs nonidentically perform, the motion transformation should be proceeded with another correlation.

At the actuator level, the modeling of SPAs has been extensively studied. The most widespread approach to handle the infinite-DOF structures of SPAs has been exploiting the combined effects of local joints to represent the SPA configurations. Many models of SPAs in which the SPA configurations are represented by curvature angle have been elaborated and presented under the condition of constant curvature. Nevertheless, SPAs inconsistently curve along their length in SPG pincer grasping. A new concept of SPA modeling is therefore needed as part of the modeling of SPG pincer grasping. Equation (2) encourages us to employ δ_S to represent the SPA configurations. The equation of motion implies that we can initiate an SPA model as follows:

$$\ddot{\delta}_S = f(\delta_S, \dot{\delta}_S, F_S, P_S), \quad (3)$$

where P_S denotes the input pressure of the SPA. Both $\dot{\delta}_S$ and $\ddot{\delta}_S$ are the derivatives with respect to time of δ_S , and f denotes a nonlinear function due to the SPA nonlinear characteristics. Equation (3) demonstrates that $\ddot{\delta}_S$ depends on δ_S , $\dot{\delta}_S$, F_S , and P_S . The SPAs are

mainly in their steady state throughout grasping. Hence, $\dot{\delta}_S$ and $\ddot{\delta}_S$ tend to be negligible. Equation (3) can be then revised as follows:

$$0 = f(\delta_S, F_S, P_S) \quad (4)$$

Equation (4) indicates that δ_S is repeatable under the identical conditions of F_S and P_S at the steady state.

2.2. Grasping Quality

Grasping quality, denoted by $\mathbf{Q}$, is essentially a kind of matrix containing parameters of grasping satisfaction and outcome. The dimension of $\mathbf{Q}$ and its components are fundamentally subjective according to individual requirements. Different parameters and indexation can be employed to determine the physical definitions of $\mathbf{Q}$. The dependence on the subjectivity of $\mathbf{Q}$ made a discussion of indexation beyond the scope of this study. However, it is well known that there are countless factors of $\mathbf{Q}$. The mathematic expression of $\mathbf{Q}$ can be then written as a matrix function as follows:

$$\mathbf{Q} = F(\mathbf{Q}_1, \mathbf{Q}_2, \dots, \mathbf{Q}_n). \quad (5)$$

where $\mathbf{Q}_i$ denotes $\mathbf{Q}$ due to each factor. The understanding of $\mathbf{Q}_i$ will advance the opportunity of modeling and controlling $\mathbf{Q}$. We focus on $\mathbf{Q}$ due to SPA performance, denoted by $\mathbf{Q}_S$, in this work. From our observation, contact area and squeezing force are the most obvious factors of $\mathbf{Q}_S$. In pincer grasping, contact area is empirically dominated by δ_O , and squeezing force is F_O by its definition. In this sense, $\mathbf{Q}_S$ is a function of δ_O and F_O as follows:

$$\mathbf{Q}_S = G(\delta_O, F_O). \quad (6)$$

Equation (6) illustrates that $\mathbf{Q}_S$ can be controlled once δ_O and F_O are intentionally programmable, and it also highlights that there is no specific physical definition of $\mathbf{Q}_S$. Additionally, the factors of $\mathbf{Q}_S$ can be further added.

2.3. Modeling Technique

The modeling technique allows us to systematically forecast $\mathbf{Q}_S$ through δ_O and F_O . The stiffness of an object, denoted by k_O , is utilized in this technique. The correlation between δ_O and F_O is governed by k_O as follows:

$$F_O = k_O \delta_O. \quad (7)$$

Basically, k_O is almost constant for rigid objects and decreases over δ_O and F_O for soft objects. Equations (1) and (2) reveal that both δ_S and F_S in Equation (7) can be replaced by δ_S and F_S , respectively, as follows:

$$F_S = k_O(\delta_S - G). \quad (8)$$

Equation (8) shows that k_O significantly influences δ_S and F_S throughout grasping. We suggest that δ_S and F_S over P_S can be forecast by solving Equations (4) and (8) together. The result of solving Equation (4) can be represented as performance curves, and the result of solving Equation (8) can be demonstrated as a stiffness curve. The solid lines in Figure 2 demonstrate the performance curves, and the dashed line in the same figure asymptotically illustrates the stiffness curve. Once we plot these curves on the same chart, the obtained intersections predictively indicate δ_S and F_S at particular conditions of P_S (Figure 2). The discrete results are then able to become continuous as δ_S and F_S over P_S using linear interpolation. Afterwards, δ_O and F_O over P_S can be obtained using Equations (1) and (2). Finally, $\mathbf{Q}_S$ over P_S is forecastable using Equation (6).

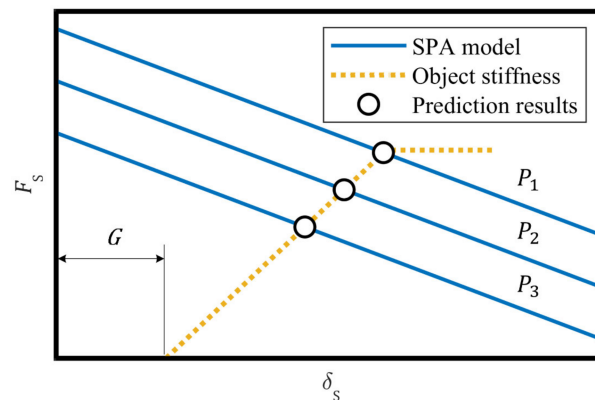


Figure 2. A modeling technique of adaptive SPG pincer grasping based on object stiffness.

The proposed technique requires SPA performance curves. Nevertheless, solving Equation (4) is challenging. No standard analytical method is available for this purpose. We accordingly conducted an empirical inspection to acquire SPA performance curves for comprehensive demonstration. Two identical industrial SPAs, the operating P_S of which ranges from -100 to 100 kPa., were employed in this inspection. The inspection proceeded using an experimental setup shown in Figure 3. The components of the setup included a motorized stage, load cell, and air supply. One of the SPAs was vertically hung, and the load cell was propelled in horizontal to adjust the limit of δ_S . The air supply was executed to provide P_S . Once the SPA reached its steady state, F_S was measured with the load cell. These procedures were iterated until F_S was obtained under all conditions of δ_S and P_S . The designated conditions of δ_S ranged from 0 to 8 mm with 200 μ m intervals, whereas those of P_S ranged from 10 to 100 kPa with 10 kPa intervals. The SPA was subsequently replaced by the other, and the whole process was repeated. The comparable results of both SPAs were averaged. Finally, the SPA performance curves were plotted.

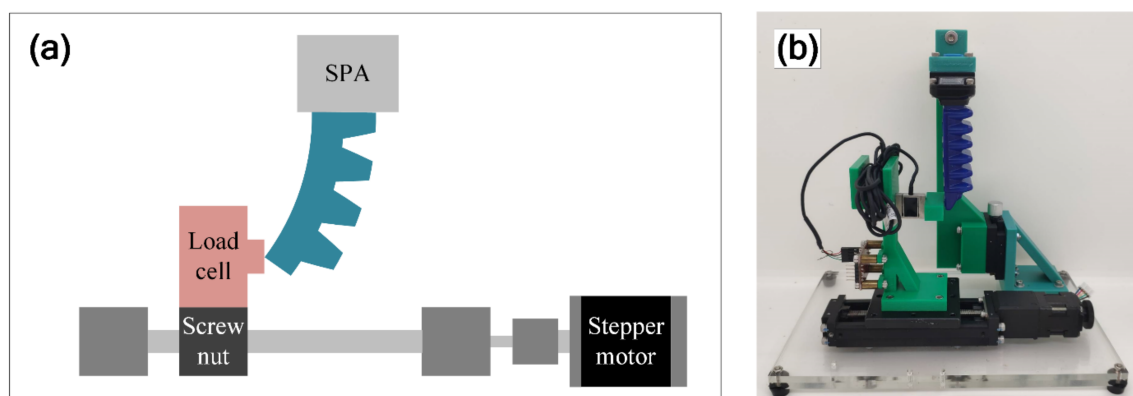


Figure 3. An experimental setup for acquiring SPA performance curves: (a) schematic and (b) photograph.

Besides SPA performance curves, an object-stiffness curve is essential in this technique. An empirical investigation for an object-stiffness curve was then initiated. The specimen object was a flexible 3D-printed object with a cylindrical shape. The investigation was implemented using an experimental setup shown in Figure 4. The setup comprised a motorized stage, load cell, and bumper. By moving the load cell, δ_O was varied. Once the object was steadily squeezed, F_O was measured with the load cell. This procedure was iterated until F_O at all designated conditions of δ_O was obtained. The designated conditions of δ_S ranged from 0 to 5 mm with 100 μ m intervals. The object-stiffness curve was finally plotted following result collection.

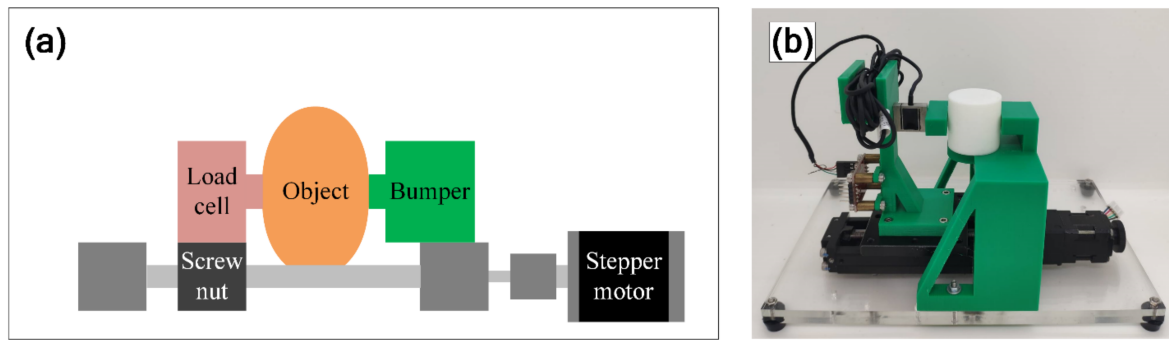


Figure 4. An experimental setup for investigating an object-stiffness curve: (a) schematic and (b) photograph.

2.4. Control Architecture

The control architecture was elaborated to accommodate desirable Q_S , denoted by Q'_S . It is essentially an open-loop architecture (Figure 5). First, Q'_S is required to be indexed in the basis of preferable δ_O and F_O , sequentially denoted by δ'_O , and F'_O . The indexation of Q_S is the key in this step, but it is not within the scope of this work due to its subjectivity. Further studies on indexation are required to fulfill this architecture. Afterwards, suitable P_S for δ'_O , and F'_O is acquired using models produced using the presented modeling technique. Then, P_S is supposed to be applied on SPAs. Both δ_S and F_S are conducted. If the SPGs and grasped objects are in an appropriate position, pincer grasping is performed, and δ_O and F_O are produced on the objects. Finally, Q_S is obtained. As an open-loop control architecture, accurate models at both actuator and task levels give more precise Q_S .

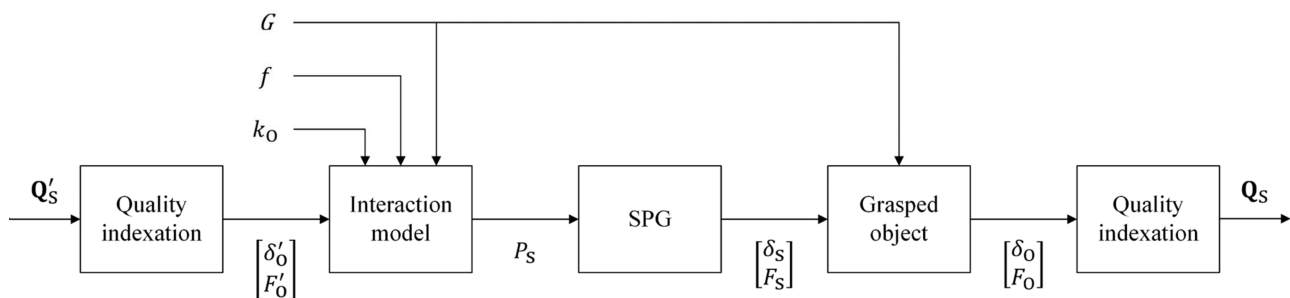


Figure 5. A control architecture of adaptive SPG pincer grasping quality based on object stiffness.

2.5. Validation

Equation (6) shows that there is no exact physical definition of Q_S . The first step of validation is defining Q_S . We decided to define Q_S as the multiplication product of δ_O and F_O . Thus, Q_S correlates to the elastic energy stored in grasped objects. The mathematic representation of Q_S can be written as follows:

$$Q_S = F_O \delta_O. \quad (9)$$

Equation (9) was used to compute Q_S from δ_O and F_O . We set the testing conditions of P_S ranging from 25 to 85 kPa with 20 kPa intervals. The modeling technique was next implemented to forecast δ_O , F_O , and Q_S over P_S . The forecast results at the specified conditions were considered as δ'_O , F'_O , and Q'_S , respectively. Practical grasping was also implemented to observe actual Q_S under the same condition of P_S , using an experimental setup shown in Figure 6. The main components of the setup included a binocular camera and air supply. The air supply was executed to provide P_S . Once the grasping became steady, stereo images of the SPG and object were captured using the binocular camera. Image processing and computer vision were utilized to determine δ_O from the images. Afterwards, the object-stiffness curve was used to obtain F_O from the determined values of δ_O . The actual results

of δ_O and F_O were employed to calculate Q_S . The deviation of Q'_S from Q_S , denoted by ΔQ_S , was exploited as the main criterion of the validation. It can be mathematically written as follows:

$$\Delta Q_S = Q'_S - Q_S. \quad (10)$$

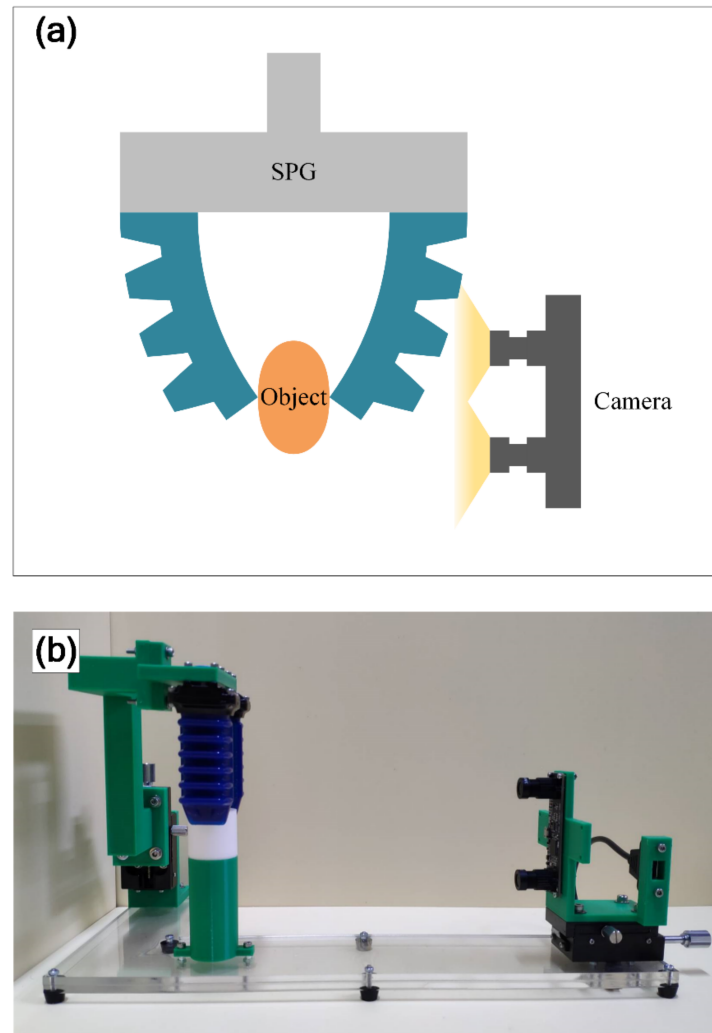


Figure 6. An experimental setup for observing adaptive SPG pincer grasping: (a) schematic and (b) photograph.

The deviations of δ'_O and F'_O , denoted by $\Delta\delta'_O$ and $\Delta F'_O$, respectively, were also validation criteria. Their mathematical representations are similar to Equation (10).

3. Results and Discussion

The first obtained results were the SPA performance curves (Figure 7). Each performance curve reveals the correlation between δ_S and F_S at a specific condition of P_S . The performance curves reveal that F_S experienced an almost linear decrease, while δ_S increased at every single condition of P_S . Both δ_S and F_S were amplified when P_S increased. Moreover, the decrease of F_S with respect to δ_S was invariant when P_S increased. The maximum value of F_S was 2.225 N when δ_S and P_S were at 0 mm and 100 kPa, respectively. The curvature of the SPAs was constant along their length when F_S was low and varied in larger magnitude when F_S became greater, during the inspection process. This phenomenon remarks the necessity of a new concept of SPA modeling.

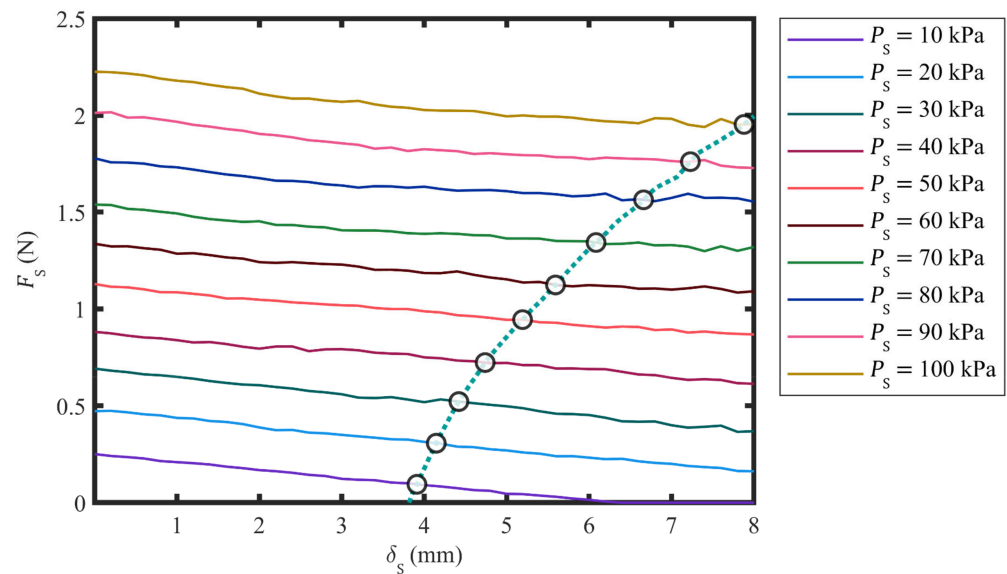


Figure 7. Performance curves of an SPA, a stiffness curve of an object, and primary prediction deformation and force of SPG pincer grasping on the object.

A stiffness curve of the specimen object was the next result collected (Figure 7). The investigation results illustrate that k_O parabolically declined, from 1.213 N/mm to 260 mN/mm, when δ_O and F_O increased.

The performance and stiffness curves were used to forecast δ_O , F_O , and Q_S over P_S . The intersections in Figure 7 predictively indicate δ_S and F_S at the SPA-inspection conditions of P_S . Afterwards, δ_O , F_O , and Q_S in the same conditions were achieved. Linear interpolation subsequently converted the discrete results into continuous δ_O , F_O , and Q_S over P_S ranging from 10 to 100 kPa (Figure 8a,c,e). Afterwards, δ'_O , F'_O , and Q'_S were determined from the prediction results. The validation experiment was then completed. The actual results of δ_O , F_O , and Q_S were obtained (Figure 8a,c,e). The predicted and actual results had a similar trend in the comparable aspect. Next, $\Delta\delta_O$, ΔF_O , and ΔQ_S at the testing conditions of P_S were acquired (Figure 8b,d,f). The comparison results show that $\Delta\delta_O$ and ΔF_O were below 464 μm and 410 mN, respectively. Furthermore, ΔQ_S was under 451 μJ . Small results of $\Delta\delta_O$, ΔF_O , and ΔQ_S proved that Q_S can be reliably modeled and controlled. The proposed modeling technique and control architecture is credible. These findings clarify the association between Q_S and P_S and, moreover, advance the development toward modellable and controllable Q .

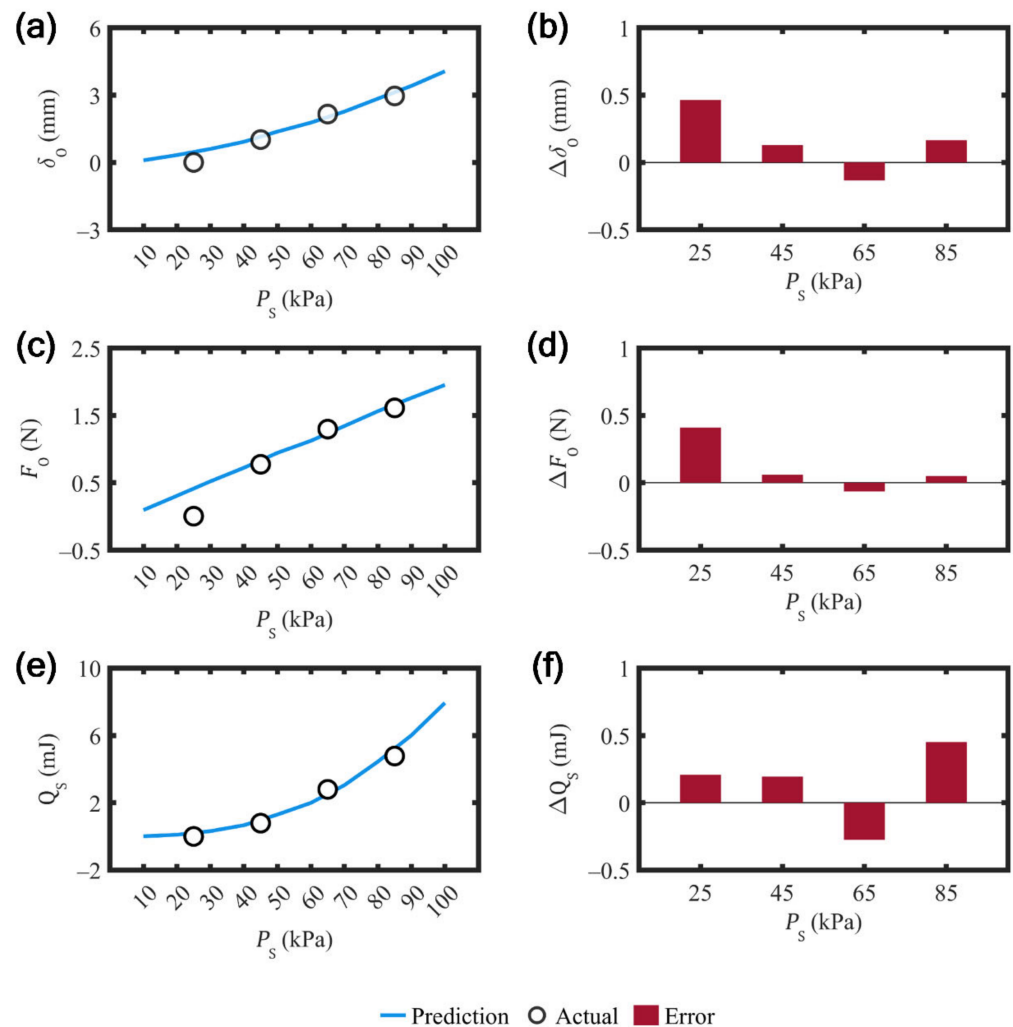


Figure 8. Results of SPG pincer grasping on an object: (a) deformation of the object; (b) deviation in deformation; (c) exerted force on the object; (d) deviation in force; (e) grasping quality due to SPA performance; and (f) deviation in grasping quality due to SPA performance.

4. Conclusions

Adaptive pincer grasping of SPGs based on object stiffness is presented in this study. The main goal of this study was to clarify the association between grasping quality and SPA performance. SPA structures have infinite DOF, so the clarification is certainly not straightforward. We ignored the effects of other factors on grasping quality and focused only on grasping quality due to SPA performance. A modeling technique and control architecture were presented for the implementation of the proposed grasping. A validation of the established methods was conducted to evaluate their reliability. The validation results show that grasping quality correlates to the input air pressure of SPAs. The same results also reveal that grasping quality due to SPA performance is modellable and controllable using the established methods. These findings proceed the advancement on the modeling and control of grasping quality in SPG pincer grasping. This is a novel study of substantial duration that considers this issue. Further study on the correlations between grasping quality and other factors is strongly recommended. Therefore, grasping quality is expected to be modellable and controllable when the effects of all significant factors are determined and accounted for in its comprehensive modeling and control.

Author Contributions: Conceptualization, C.S.; methodology, C.S.; software, C.S.; validation, C.S.; formal analysis, C.S.; investigation, C.S.; resources, C.S. and R.C.; data curation, C.S.; writing—original draft preparation, C.S.; writing—review and editing, C.S.; visualization, C.S.; supervision, R.C.; project administration, C.S. and R.C.; funding acquisition, R.C. All authors have read and agreed to the published version of the manuscript.

Funding: This project is funded by National Research Council of Thailand (NRCT).

Acknowledgments: C.S. is supported by a scholarship from “The 100th Anniversary Chulalongkorn University Fund for Doctoral Scholarship”.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Tsai, R.Y. A New Technique for Fully Autonomous and Efficient 3d Robotics Hand/Eye Calibration. *IEEE Trans. Robot. Autom.* **1989**, *5*, 345–358. [\[CrossRef\]](#)
2. Levine, S.; Pastor, P.; Krizhevsky, A.; Ibarz, J.; Quillen, D. Learning Hand-Eye Coordination for Robotic Grasping with Deep Learning and Large-Scale Data Collection. *Int. J. Robot. Res.* **2018**, *37*, 421–436. [\[CrossRef\]](#)
3. Piazza, C.; Grioli, G.; Catalano, M.G.; Bicchi, A. A Century of Robotic Hands. *Annu. Rev. Control Robot. Auton. Syst.* **2019**, *2*, 1–32. [\[CrossRef\]](#)
4. Marwan, Q.M.; Chua, S.C.; Kwek, L.C. Comprehensive Review on Reaching and Grasping of Objects in Robotics. *Robotica* **2021**, *39*, 1849–1882. [\[CrossRef\]](#)
5. Han, L.; Trinkle, J.C.; Li, Z.X. Grasp Analysis as Linear Matrix Inequality Problems. *IEEE Trans. Robot. Autom.* **2000**, *16*, 663–674. [\[CrossRef\]](#)
6. Miller, A.T.; Allen, P.K. Graspit: A Versatile Simulator for Robotic Grasping. *IEEE Robot. Autom. Mag.* **2004**, *11*, 110–122. [\[CrossRef\]](#)
7. Bohg, J.; Morales, A.; Asfour, T.; Kragic, D. Data-Driven Grasp Synthesis—a Survey. *IEEE Trans. Robot.* **2014**, *30*, 289–309. [\[CrossRef\]](#)
8. Zhang, B.; Xie, Y.; Zhou, J.; Wang, K.; Zhang, Z. State-of-the-Art Robotic Grippers, Grasping and Control Strategies, as Well as Their Applications in Agricultural Robots: A Review. *Comput. Electron. Agric.* **2020**, *177*, 105694. [\[CrossRef\]](#)
9. Bao, G.; Fang, H.; Chen, L.; Wan, Y.; Xu, F.; Yang, Q.; Zhang, L. Soft Robotics: Academic Insights and Perspectives through Bibliometric Analysis. *Soft Robot.* **2018**, *5*, 229–241. [\[CrossRef\]](#)
10. Boyraz, P.; Runge, G.; Raatz, A. An Overview of Novel Actuators for Soft Robotics. *Actuators* **2018**, *7*, 48. [\[CrossRef\]](#)
11. Hughes, J.; Culha, U.; Giardina, F.; Guenther, F.; Rosendo, A.; Iida, F. Soft Manipulators and Grippers: A Review. *Front. Robot. AI* **2016**, *3*, 69. [\[CrossRef\]](#)
12. Hines, L.; Petersen, K.; Lum, G.Z.; Sitti, M. Soft Actuators for Small-Scale Robotics. *Adv. Mater.* **2017**, *29*, 1603483. [\[CrossRef\]](#)
13. Polygerinos, P.; Correll, N.; Morin, S.A.; Mosadegh, B.; Onal, C.D.; Petersen, K.; Cianchetti, M.; Tolley, M.T.; Shepherd, R.F. Soft Robotics: Review of Fluid-Driven Intrinsically Soft Devices; Manufacturing, Sensing, Control, and Applications in Human-Robot Interaction. *Adv. Eng. Mater.* **2017**, *19*, 1700016. [\[CrossRef\]](#)
14. Lipson, H. Challenges and Opportunities for Design, Simulation, and Fabrication of Soft Robots. *Soft Robot.* **2014**, *1*, 21–27. [\[CrossRef\]](#)
15. Chen, X.; Zhang, X.; Huang, Y.; Cao, L.; Liu, J. A Review of Soft Manipulator Research, Applications, and Opportunities. *J. Field Robot.* **2022**, *39*, 281–311. [\[CrossRef\]](#)
16. Su, H.; Hou, X.; Zhang, X.; Qi, W.; Cai, S.; Xiong, X.; Guo, J. Pneumatic Soft Robots: Challenges and Benefits. *Actuators* **2022**, *11*, 92. [\[CrossRef\]](#)
17. Thuruthel, T.G.; Ansari, Y.; Falotico, E.; Laschi, C. Control Strategies for Soft Robotic Manipulators: A Survey. *Soft Robot.* **2018**, *5*, 149–163. [\[CrossRef\]](#)
18. Suzumori, K.; Iikura, S.; Tanaka, H. Applying a Flexible Microactuator to Robotic Mechanisms. *IEEE Control Syst.* **1992**, *12*, 21–27.
19. Godage, I.S.; Wirz, R.; Walker, I.D.; Webster, R.J. Accurate and Efficient Dynamics for Variable-Length Continuum Arms: A Center of Gravity Approach. *Soft Robot.* **2015**, *2*, 96–106. [\[CrossRef\]](#)
20. Polygerinos, P.; Wang, Z.; Overvelde, J.T.B.; Galloway, K.C.; Wood, R.J.; Bertoldi, K.; Walsh, C.J. Modeling of Soft Fiber-Reinforced Bending Actuators. *IEEE Trans. Robot.* **2015**, *31*, 778–789. [\[CrossRef\]](#)
21. Gerboni, G.; Diodato, A.; Ciuti, G.; Cianchetti, M.; Mencias, A. Feedback Control of Soft Robot Actuators via Commercial Flex Bend Sensors. *IEEE/ASME Trans. Mechatron.* **2017**, *22*, 1881–1888. [\[CrossRef\]](#)
22. Hao, Y.; Wang, T.; Ren, Z.; Gong, Z.; Wang, H.; Yang, X.; Guan, S.; Wen, L. Modeling and Experiments of a Soft Robotic Gripper in Amphibious Environments. *Int. J. Adv. Robot. Syst.* **2017**, *14*, 1729881417707148. [\[CrossRef\]](#)
23. Wang, Z.; Hirai, S. Soft Gripper Dynamics Using a Line-Segment Model with an Optimization-Based Parameter Identification Method. *IEEE Robot. Autom. Lett.* **2017**, *2*, 624–631. [\[CrossRef\]](#)
24. Elgeneidy, K.; Lohse, N.; Jackson, M. Bending Angle Prediction and Control of Soft Pneumatic Actuators with Embedded Flex Sensors—A Data-Driven Approach. *Mechatronics* **2018**, *50*, 234–247. [\[CrossRef\]](#)
25. Hainsworth, T.; Smith, L.; Alexander, S.; MacCurdy, R. A Fabrication Free, 3d Printed, Multi-Material, Self-Sensing Soft Actuator. *IEEE Robot. Autom. Lett.* **2020**, *5*, 4118–4125. [\[CrossRef\]](#)

26. Abbasi, P.; Nekoui, M.A.; Zareinejad, M.; Abbasi, P.; Azhang, Z. Position and Force Control of a Soft Pneumatic Actuator. *Soft Robot.* **2020**, *7*, 550–563. [[CrossRef](#)]
27. Tian, Y.; Zhang, Q.; Cai, D.; Chen, C.; Zhang, J.; Duan, W. Theoretical Modelling of Soft Robotic Gripper with Bioinspired Fibrillar Adhesives. *Mech. Adv. Mater. Struct.* **2020**, *29*, 2250–2266. [[CrossRef](#)]
28. Ibrahim, S.; Krause, J.C.; Olbrich, A.; Raatz, A. Modeling and Reconstruction of State Variables for Low-Level Control of Soft Pneumatic Actuators. *Front. Robot. AI* **2021**, *8*, 557830. [[CrossRef](#)]
29. Roa, M.A.; Suárez, R. Grasp Quality Measures: Review and Performance. *Auton. Robot.* **2015**, *38*, 65–88. [[CrossRef](#)]
30. Liu, Y.; Jiang, D.; Tao, B.; Qi, J.; Jiang, G.; Yun, J.; Huang, L.; Tong, X.; Chen, B.; Li, G. Grasping Posture of Humanoid Manipulator Based on Target Shape Analysis and Force Closure. *Alex. Eng. J.* **2022**, *61*, 3959–3969. [[CrossRef](#)]
31. Zhou, H.; Tawk, C.; Alici, G. A 3d Printed Soft Robotic Hand with Embedded Soft Sensors for Direct Transition between Hand Gestures and Improved Grasping Quality and Diversity. *IEEE Trans. Neural Syst. Rehabil. Eng.* **2022**, *30*, 550–558. [[CrossRef](#)]
32. Zheng, Y. An Efficient Algorithm for a Grasp Quality Measure. *IEEE Trans. Robot.* **2013**, *29*, 579–585. [[CrossRef](#)]
33. Park, W.; Seo, S.; Oh, J.; Bae, J. A Sensorized Hybrid Gripper to Evaluate a Grasping Quality Based on a Largest Minimum Wrench. *IEEE Robot. Autom. Lett.* **2020**, *5*, 3243–3250. [[CrossRef](#)]
34. Udupa, G.; Sreedharan, P.; Dinesh, P.S.; Kim, D. Asymmetric Bellow Flexible Pneumatic Actuator for Miniature Robotic Soft Gripper. *J. Robot.* **2014**, *2014*, 902625. [[CrossRef](#)]
35. Yang, H.; Chen, Y.; Sun, Y.; Hao, L. A Novel Pneumatic Soft Sensor for Measuring Contact Force and Curvature of a Soft Gripper. *Sens. Actuators A Phys.* **2017**, *266*, 318–327. [[CrossRef](#)]
36. Lotfiani, A.; Yi, X.; Shao, Z.; Zhao, H.; Parkestani, A.N. Analytical Modeling and Optimization of a Corrugated Soft Pneumatic Finger Considering the Performance of Pinch and Power Grasps. *Extrem. Mech. Lett.* **2021**, *44*, 101215. [[CrossRef](#)]
37. Alici, G.; Canty, T.; Mutlu, R.; Hu, W.; Sencadas, V. Modeling and Experimental Evaluation of Bending Behavior of Soft Pneumatic Actuators Made of Discrete Actuation Chambers. *Soft Robot.* **2018**, *5*, 24–35. [[CrossRef](#)]