A Soft and Smart Telehealth System: Hand Rehabilitation Device for Grasping Force Assessment of Post Stroke Patients

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Abstract—This study introduces a sensorised device designed to address current shortcomings of post-stroke patient rehabilitation assessment. The device interfaces with a platform allowing therapists to visually analyse real-time data and retrieve it for an in-depth analysis. The study details the development and characterisation of Pneumatic Sensing Chambers (PSCs) using Finite Element Analysis (FEA) and mechanical testing. After selection and integration, the sensors were incorporated into a compact, portable object with communication established via multiplexers and an Arduino Nano. The system was connected to a laptop using LabView for user interface. It allows concurrent measurement of finger forces during grasping movements for both hands, with real-time visualization and data retrieval support. The device offers a cost-effective, precise, and adaptable solution, with potential for further enhancements in precision, durability, and applicability in stroke rehabilitation scenarios. This tool has the capacity to significantly enhance rehabilitation strategies and aid in the recovery process.

Index Terms—Stroke, Hand rehabilitation, Sensorised objects, Grasping force, Flexible sensors

I. INTRODUCTION

Stroke is a major global health issue, causing high mortality and disability rates [1], [2]. Survivors often face challenges, especially with motor skills, causing long term consequences for patients and their families [3]. With the increasing stroke burden and healthcare constraints, telehealth systems, including self-directed rehabilitation, are promising solutions [4], [5]. These services should incorporate self-directed rehabilitation strategies, making them accessible in both community and home-based therapy settings [5]. Moreover, to enrich neurorehabilitation and improve stroke outcome in general, it is crucial to address the underlying recovery process since observational analysis on itself is not sufficient to measure the patient's improvement [6].

Recent advancements in sensor technology allows for realtime monitoring and feedback in home-based therapy, potentially improving patient engagement and outcomes [3], [7], offering cost savings for healthcare services, increasing therapy intensity, and ultimately enhancing rehabilitation outcomes [3], [8]–[10]. Within the context of hand rehabilitation for stroke patients, numerous methods exist. These include conventional approaches such as occupational therapy, and physical therapy, as well as emerging innovative techniques and commercially available devices that are currently undergoing clinical experimental studies. Examples of these new methods include robotics, virtual reality, telerehabilitation devices, cellular therapy, and others [8], [9], [12]. Despite the variety of approaches available, there is still a significant gap when it comes to quantitatively measuring patients' progress in rehabilitation therapy. The field is far from having a universally accepted system for quantifying and classifying hand functional improvement [13].

The commonly used Fugl-Meyer Assessmen (FMA) scales, while widely utilised, suffer from subjectivity, requiring previous experience and expertise from a healthcare professional [13], lack of meaningful quantitative data on progress [14] and can be time-consuming, necessitating the presence of a professional for a period of 30 minutes [11]. Goniometers are tools used for assessing FMA scales, but they face accuracy issues and are slow when evaluating multiple joint angles. Dynamometers, while common and reliable, are unable to assess individual finger performance, which is crucial for personalized rehabilitation.

Commercial hand rehabilitation devices, including exoskeletons and end-effector devices, can assess crucial metrics such as Range of Motion (ROM), force, spasticity, movement speed, coordination, and progress in task execution. Nevertheless, these solutions can be expensive, bulky, and require professional supervision [15]–[17]. Additionally, for stroke patients, wearability can be a concern given the varying levels of impairment.

In response to the limitations associated with traditional and commercially available solutions, sensorised objects have emerged as promising alternatives, offering practicality, versatility, and lower production costs. These objects are equipped with robust sensors prioritizing accuracy and durability, overcoming the shortcomings of conventional approaches for grasping force measurements [18]. However, it's important to note that commercially available sensorised objects are currently limited, and there are still some drawbacks that need to be addressed to fully realize their potential. In [19], there is a high sensor resolution but it cannot measure finger force contribution independently. Similarly, the design presented in [20] has fixed contact areas, limiting grasping options to match the sensorised areas. [21] explored independent finger measurements, but

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fixed contact remains a limitation. [22] lacked the ability to measure grasping force intensity. These limitations emphasize the need for more advanced and comprehensive rehabilitation methods that address individual finger measurement, flexibility, accurate force measurement, and a personalized approach to stroke rehabilitation.

This lack of a standardised system hinders our ability to confirm and validate the effectiveness of each emerging therapy method in improving patient outcomes. Therefore, the objective of this work is to address the persistent challenge of improving upper limb function in stroke patients faster, despite the extensive research conducted on rehabilitation interventions. To address this challenge, a sensorised object was developed, and its embedded sensors were systematically designed, fabricated, and characterised. Subsequently, the system was integrated with LabVIEW, facilitating a user-friendly and quantitative interface. This interface holds the potential for therapists to utilise the system, providing them with the ability to understand the patient's needs more easily, ultimately assisting healthcare professionals in streamlining the customisation of therapy exercises right from the outset of the process.

II. MATERIALS AND METHODS

A. Design Principles

The PSCs were designed using Autodesk Fusion 360 (Autodesk Inc.), with approximately 10 different shapes considered. However, only the three designs presented in Figure 1 underwent testing, as specific design criteria needed to be met. The other seven designs were found inadequate for this application as they presented sharp edges and corners, sizes too large to implement on the cylinder, which would be hard to grasp for an average hand size, and would reduce the number of sensors that could be included for higher resolution. These were designated as S2 (a larger half sphere), E1 (a small half ellipsoid), and S1 (a small half sphere with the same inner volume as E1). These selections were made to ensure that the patient could easily grasp the object and to enable precise pressure measurement. Therefore, it was necessary to avoid sharp corners, where the measured force would vary depending on the region where the patient touched the sensor. Designs with sharp edges and areas subjected to high stress were avoided. To prevent any potential air leakage, a minimum wall thickness of 1mm was implemented. Additionally, all sensors were constrained to dimensions of 30x30x15mm, striking a careful balance between the sensitivity of the sensor and the resolution in the number of sensors occupied per unit of space when further incorporated into a cylinder.

B. 3D Printing

The 3D CAD designs were prepared for printing using Simlify3D (Simplify3D Inc.), optimized for flexible filaments. Additional adjustments were made to ensure printing quality and prevent air leakage in spherical shapes, as detailed in Table I. The resulting files were exported for use with a Flash-Forge Inventor (FlashForgeInventor, FlashForge Corporation) Fused Deposition Modeling 3D printer, using a Thermoplastic formed using the Honeywell ABPDANT005PGAA5 piezore-



Fig. 1. Schematic of the PSCs design improvements (a) S2, (b) E1, (c) S1, (d) S2 Sizes - A: 15mm, B: 30mm, C: 1mm , D: 4mm, (e) E1 Sizes - A: 10mm, B: 35mm, C: 1mm, (f) S1 Sizes - A: 10mm, B: 26mm, C: 1mm, D: 2.5mm



Fig. 2. Improvements achieved through the optimisation of the manufacturing process detailed inI.

polyurethane (TPU) filament, NinjaFlex (NinjaTek, USA). Figure 2 presents the 3D-printed enhancements achieved through the optimised parameter process.

TABLE I OPTIMIZED PARAMETERS FOR 3D-PRINTED AIRTIGHT SPHERICAL SURFACES

Parameters	Value	Unit
Resolution Settings		
Width	0.45	mm
Top Solid Layers	10	
Bottom Solid Layers	4	
Infill Settings		
Internal Fill Pattern	Full Honeycomb	
External Fill Pattern	Concentric	
Internal Fill Angle Offsets	+/-120	0
Outline Overlap	80	%

C. Experimental Hardware and Setup

To validate sensor accuracy, displacement tests were per-



Fig. 3. Experimental tests setup (a) Static weight test - (1) Dead Weight, (2) Additional designed support and (b) UTM dynamic tests - (1) UTM Cell, (2) PSC, (3) Designed upport, (4) Pressure Sensor connected to the PSC and cables

sistive silicon pressure sensor (HoneywellInternational Inc), known for its precision and stability. It was attached to the PSC using a commercially available speedfit water pipe and a fabric airtight glue, and linked to an Arduino NANO (Arduino, version 2.1.1., Inc) for data conversion into kPa. Two tests were conducted: static (for stability over time), using a dead weight, and dynamic (for linearity, hysteresis, repeatability, lifetime, and durability), using a Universal Testing Machine (UTM) as shown in Figure 3. The Software "TrapeziumX" () recorded deformation and force, while Arduino measured and recorded pressure through the CoolTerm (Cool).

D. Finite Element Modeling

ANSYS Workbench (Release 23.1, ANSYS, Inc.) was utilized for in-depth hyper-elastic material analysis of the designed CAD models. A "Static structural analysis" was conducted to assess sensitivity, and optimize load-displacement relationship.

1) Material: To perform this analysis, a commercially available Thermoplastic poly(urethane) (TPU) known as "Ninja Flex" was imported from the "Engineering Data" library. The TPU was characterised as a hyperelastic material through the use of The Mooney-Rivlin five-parameter model, which was determined based on the mean stress-strain data obtained from previous experiments [23].

2) Meshing: An adaptive meshing technique using the "Tetrahedron" method ensured accuracy, efficiency, and convergence on curved surfaces. To strike a balance between accuracy and computational efficiency for this material, the "Body sizing" parameter was applied to the Spherical and Elliptical surfaces of the sensors with a 1.2 mm element size, given the suitability of a coarser mesh for hyper-elastic materials. The mesh size adequacy was verified through a convergence study, which analyzed the system with varying mesh sizes, ensuring consistent and minimally variable results.

3) Boundary Conditions: Automated frictionless contact pairs were established for files with a flat surface cylinder, simulating the UTM, and PSC. Time step controls used "Automatic bisection" to avoid convergence issues. A "Fixed Support" was applied to the PSC's bottom face, simulating the contact with the UTM base, where the PSC's were later tested. For files with



Fig. 4. Stability over time experimental results

the PSC and a cylindrical surface, directional displacements were applied for a realistic UTM simulation. For PSC-only files, a 2 mm perpendicular displacement was applied at 45° for stress points analysis.

4) Analysis Setup: For accurate solutions in nonlinear static analyses, "Automatic time stepping" with 10 substeps was used to prevent convergence issues. "Large deflection" was enabled to address anticipated large deformations and geometric nonlinearity, preventing significant alterations in stiffness and stress distribution that could impact the results. To stabilize the model, "Weak springs" were introduced in frictionless contact assemblies. The FEA results are presented together with some experimental results in the next section in Figures 6 and 7.

III. RESULTS

A. Stability Over Time

1) Materials and Methods: Figure 4 shows the stability test results over 30 minutes with a 1 Kg weight applied.

2) *Results:* Initially, there was a slight increase in readings, likely due to material relaxation. However, after 2 minutes, no significant fluctuations were observed.

3) Discussion: The stable signals confirm the air-tightness of the system, ensuring reliable and consistent data, crucial for PSC effectiveness.

B. Linearity

Figure 5 depicts the correlation between pressure readings and applied load for different sensor shapes.

1) Materials and Methods: To ensure accuracy, a 5-second waiting time was observed before recording the pressure corresponding to the load step applied, ranging from 0 to 15 N with an increment of 2.5 N.

2) *Results:* Linear fitting in MATLAB resulted in coefficients of determination: $R^2 = 0.9928$ for S2, $R^2 = 0.9618$ for E1, and $R^2 = 0.9908$ for S1.

3) Discussion: Spheres exhibited superior linearity, making S2 and S1 spheres more favorable in this test. S2 shape had lower sensitivity due to its larger inner volume. However, when shapes with equivalent inner volumes were subjected to the same load, notable pressure variations were observed: S1 (0 to 23 kPa) compared to E1 (0 to 13 kPa).

We postulate that not only the inner volume, but also the geometric shape of the chambers affect the pressure range and



Fig. 5. Linear regression of static weight test results: Blue-S2, Yellow-E1, Red-S1

the sensitivity of the chambers. This is a finding requiring further investigation.

C. Hysteresis

To compare the relationship between the experimental values with the FEA and to understand its accuracy, the graph from Figure 6 presents the linearity between FEA volume ratio, V1/V2, and its corresponding output pressure measured from the PSCs as the displacement was ramped up and down. P1 and V1 are the initial pressure and volume, respectively, and P2 and V2 are the pressure and volume after corresponding displacement, respectively.

This relationship can be described as the inverse relationship between pressure and volume of a gas at constant temperature, which is known as Boyle's Law [24] given by the equation:

$$P_1 V_1 = P_2 V_2 \tag{1}$$

The primary objective of this graph is to provide evidence of the accuracy of the developed FEA. Due to the small size of the PSC and the minute displacements under study, even the slightest variation can result in higher variations, which can explain the more pronounced disparities observed between FEA and experimental results when subjected to smaller displacements.

Regarding the output pressure, all PSCs exhibited minimal hysteresis, a critical factor in preventing reading errors and maintaining recording stability. As observed in Subsection III-B, Spheres demonstrated a more linear and predictable behavior compared to the ellipsoid, as indicated by the coefficient of determination.

Accurate sensing is vital in soft robotics for human interaction. Minimal hysteresis ensures consistent and responsive feedback, particularly during fast or unpredictable movements. The results support existing literature [23], [25], underscoring the effectiveness of these sensing mechanisms, with the potential to enhance patient care and comfort.

The displacement and correspondent force in both FEA and experimental results are presented in Figure 7. When considering the force required to generate a specific output pressure, it a 1Kg weight to the sensors for 5 minutes. Figure 10 depicts is observed that spherical shapes require less force compared the measurements taken during this test.

to the ellipsoid for the same displacement. However, in case of S1 and E1 having the same inner volume, a significantly greater force is required for E1 to achieve the same pressure variation. As a consequence, it is evident that the small sphere is the shape selected for the sensorised object presented in the next section.

The influence of stiffness in S2 is apparent in the data. The experimental results show a smooth curve for S2, which can be attributed to the walls of S2 offering increased resistance beyond 1.5mm of compression. This leads to two distinct reaction force behaviours: the first one with a smaller linear slope up to 1.5mm, and the second one with a steeper linear slope beyond that threshold.

In contrast, both E1 and S1 exhibit a more linear behavior. The coefficient of determination for the experimental results corresponds to $R^2 = 0.942$ and $R^2 = 0.925$ for the ramped-up and ramped-down results of shape S2; E1 presented $R^2 = 0.997$ and $R^2 = 0.981$ for the ramped-up and ramped-down phases, respectively. For shape S1, $R^2 = 0.980$ for the ramped-up phase and $R^2 = 0.995$ for the ramped-down phase.

In this scenario, the reaction force observed in FEA was unable to predict the behavior of the material, leading to significant discrepancies from reality. Additionally, the printing quality also had an impact on the shapes' behavior during the experimental tests, resulting in differences from the original CAD models used in the FEA.

Figure 8 demonstrates 500 activation cycles with no discernible drift. All shapes maintained high consistency throughout, showcasing the PSCs' exceptional robustness. This enhances system reliability and performance, reducing maintenance costs and minimizing downtime.

IV. SYSTEM DESIGN

A. Proposed Layout

The S1 PSC was chosen due to its small and compact shape, along with the higher sensitivity, making it the most suitable for the application. A schematic layout was developed using 19 S1 PSCs around a cylinder with a diameter of 7 cm and a height of 13 cm. In Figure 9, a schematic of the final prototype and the map of the sensor distribution in the right and left hand are presented.

B. Calibration Procedure

To ensure a connection between the PSC and transducer, a small plastic tube was used to isolate the sensor's structure from the applied force. However, variations in tube size and placement led to discrepancies in the inner volume among the PSCs. This necessitated individual testing of each sensor to assess its force behavior at different output pressures and mitigate the risk of inaccurate readings.

Displacement tests were conducted at 0.5, 1, 1.5, and 2 mm, with each position held for 10 seconds to achieve a stable pressure value.

Furthermore, stability over time tests were carried out on each PSC to confirm their airtightness. This involved applying



Fig. 6. Linearity between FEM volume ratio and experimentally measured relative pressure (a) S2, (b) E1, (c) S1.



Fig. 7. Comparison of force over displacement between FEA and experimental results (a) S2, (b) E1, (c) S1.



Fig. 8. Repeatability experimental results over 500 cycles (a) S2, (b) E1, (c) S1.



Fig. 9. Schematic (a) Cylinder and (b) Hand map: left hand in green PSC and right hand in extra pink PSC

C. System Architecture

Two CD4051BE multiplexers with 8 input channels each were used, connecting analog signals from 16 sensors to the Arduino board, while the remaining 3 were directly connected to the Arduino. Additionally, a calibration button was incorporated to simplify the process of zeroing each sensor before conducting measurements. Figure 11 displays the developed



Fig. 10. Calibration Curves (a) Stability over 5 minutes with 1 Kg weight (b) Force versus output pressure for each PSC - Numbers are not presented in sequential order, as multiple sensors were tested and only the best 19 were selected, with others mainly presenting air leakage. For the purpose of the research and the subsequent use of the PSCs, the numbers were presented according to the parts' numbering when they were printed

prototype.

V. DISCUSSION AND CONCLUSION

Several PSCs were designed, manufactured, and characterised using FEA and mechanical tests. The results showed



Fig. 11. Sensorised Cylinder

that all designed PSCs performed well, demonstrating good stability, linearity, repeatability, negligible hysteresis, and long-lasting durability, making them reliable and accurate.

Among the shapes, S2 exhibited lower sensitivity, requiring greater pressure changes for the same displacement or force. E1 showed improved sensitivity but had the drawback of varying output pressure values based on touch location. S1 demonstrated the highest sensitivity and a uniformly curved surface, addressing the edge sensitivity issue, making it the superior choice. Shape S1 was selected for further development in the project.

After complete characterisation, multiple S1 PSCs were 3D-printed, calibrated, and integrated into the final cylinder, demonstrating crucial attributes of stability over time and linearity.

In conclusion, this research introduces a sensor-enhanced object for evaluating grasping force and distribution, overcoming previous limitations. The study has demonstrated successful design, modeling, and manufacturing of PSC with sensitive and reliable behavior. Future work involves mapping the PSC readings into individual finger forces and resultant grasping force, which holds potential for further accuracy and applicability in stroke rehabilitation, ultimately benefiting patient outcomes.

Challenges include air leakage during pressure sensor assembly, which can be addressed with a smaller sensor or alternative assembly process in future work. Exploring different 3D-printing techniques and materials for improved flexibility and sensitivity is also recommended, especially for post-stroke patients with limited force range. Additionally, considering different calibration tests to more accurately replicate the human body's contact areas and exploring alternative software platforms, such as Python, for improved display speed and visual appeal are points of focus in future work. These enhancements could lead to further accuracy and applicability in stroke rehabilitation, ultimately benefiting patient outcomes.

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REFERENCES

- R. Lozano, M. N. K. Foreman, S. Lim, et al., "Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: A systematic analysis for the global burden of disease study 2010," The Lancet, vol. 380, pp. 2095–2128, 9859 2012-12.
- [2] "Disability-adjusted life years (dalys) for 291 diseases and injuries in 21 regions, 1990-2010: A systematic analysis for the global burden of disease study 2010," Lancet (London, England), vol. 380, pp. 2197–2223, 9859 2012-12.

- [3] P. Langhorne, J. Bernhardt, and G. Kwakkel, "Stroke rehabilitation," Lancet (London, England), vol. 377, pp. 1693–1702, 9778 2011.
- [4] "Global, regional, and country-specific lifetime risk of stroke, 1990–2016," The New England Journal of Medicine, vol. 379, p. 2429, 25 2018-12.
- [5] B. Sheng, J. Zhao, Y. Zhang, S. Xie, and J. Tao, "Commercial devicebased hand rehabilitation systems for stroke patients: State of the art and future prospects," Heliyon, vol. 9, e13588, 2023.
- [6] C. Grefkes, C. Grefkes, G. R. Fink, and G. R. Fink, "Recovery from stroke: Current concepts and future perspectives," Neurological Research and Practice, vol. 2, pp. 1–10, 1 2020-06.
- [7] F. Bressi, F. Santacaterina, L. Cricenti, et al., "Robotic-assisted hand therapy with gloreha sinfonia for the improvement of hand function after pediatric stroke: A case report," Applied Sciences, vol. 12, p. 4206, 9 2022-04.
- [8] K. E. Laver, B. Lange, S. George, J. E. Deutsch, G. Saposnik, and M. Crotty, "Virtual reality for stroke rehabilitation," The Cochrane database of systematic reviews, vol. 11, 11 2017-11.
- [9] C. R, P. F, M. A, et al., "Design strategies to improve patient motivation during robot-aided rehabilitation. journal of neuroengineering and rehabilitation," Journal of Neuroengineering and Rehabilitation, 2007-12.
- [10] C. J. Winstein, J. Stein, R. Arena, et al., "Guidelines for adult stroke rehabilitation and recovery: A guideline for healthcare professionals from the american heart association/american stroke association," Stroke, vol. 47, e98–e169, 6 2016-06.
- [11] D. J. Gladstone, C. J. Danells, and S. E. Black, "The fugl-meyer assessment of motor recovery after stroke: A critical review of its measurement properties," Neurorehabilitation and Neural Repair, vol. 16, pp. 232–240, 3 2002.
- [12] D. J. Lin, S. P. Finklestein, and S. C. Cramer, "New directions in treatments targeting stroke recovery," Stroke, vol. 49, p. 3107, 12 20
- [13] R. Kabir, S. H. Sunny, H. U. Ahmed, and M. H. Rahman, "Micromachines hand rehabilitation devices: A comprehensive systematic review," A Comprehensive Systematic Review. Micromachines, vol. 13, p. 1033, 20
- [14] J. C. Hobart, S. J. Cano, J. P. Zajicek, and A. J. Thompson, "Rating scales as outcome measures for clinical trials in neurology: Problems, solutions, and recommendations," The Lancet. Neurology, vol. 6, pp. 1094–1105, 12 2
- [15] B. Sheng, J. Zhao, Y. Zhang, S. Xie, and J. Tao, "Commercial devicebased hand rehabilitation systems for stroke patients: State of the art and future prospects," Heliyon, vol. 9, e13588, 20
- [16] "Amadeo tyromotion." (), [Online]. Available: https://tyromotion.com/en/ products/amadeo
- [17] "Cybergrasp cyberglove systems llc." (), [Online]. Available: http:// www.cyberglovesystems.com/cybergrasp
- [18] B. Stephens-Fripp, E. Wallace, T. Searle and G. Alici, "Design of a Sensorised Object to Test Sensory Feedback for Prosthetic Hands," 2019 IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM), Hong Kong, China, 2019, pp. 157-162
- [19] R. Kõiva, R. Haschke, and H. Ritter, "Development of an intelligent object for grasp and manipulation research," IEEE 15th International Conference on Advanced Robotics: New Boundaries for Robotics, ICAR 2011, pp. 204–210, 201
- [20] R. A. Romeo, F. Cordella, L. Zollo, et al., "Development and preliminary testing of an instrumented object for force analysis during grasping," Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, pp. 6720–6723, 2015-1
- [21] F. Cordella, F. Taffoni, L. Raiano, et al., "Design and development of a sensorized cylindrical object for grasping assessment," Proceedings of the Annual International Conference of the IEEE Engineering in Medicine and Biology Society, EMBS, vol. 2016-October, pp. 3366–3369, 2016-
- [22] G. Gao, G. Gorjup, R. Yu, P. Jarvis, and M. Liarokapis, "Modular, accessible, sensorized objects for evaluating the grasping and manipulation capabilities of grippers and hands," IEEE Robotics and Automation Letters, vol. 5, pp. 6105–6112, 4 2020-10.
- [23] C. Tawk, G. M. Spinks, M. I. H. Panhuis, and G. Alici, "3d printable linear soft vacuum actuators: Their modeling, performance quantification and application in soft robotic systems," IEEE/ASME Transactions on Mechatronics, vol. 24, pp. 2118–2129, 5 2019-10.
- [24] E. T. Gilbert-Kawai, M. D. Wittenberg, W. (W. L. Davies, and R. Gilbert, Essential equations for anaesthesia : key clinical concepts for the FRCA and EDA. Cambridge University Press, 2014, p. 199.
- [25] D. Gong, R. He, J. Yu, and G. Zuo, "A pneumatic tactile sensor for co-operative robots," Sensors (Switzerland), vol. 17, 11 2017-