Instrumented Orthosis for Movement Evaluation and Monitoring in Hand Rehabilitation

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Abstract: Hand motor impairments can severely limit the ability to perform everyday tasks, compromising autonomy and overall quality of life. This paper presents the design of an instrumented 3D-printed hand orthosis, entirely fabricated using Thermoplastic Polyurethane (TPU) for flexibility and comfort, and equipped with resistive force and flex sensors to assess hand movements quantitatively. The orthosis allows real-time tracking of finger motions and force exertion during rehabilitation and grasping tasks. It also provides remote access to health professionals for rehabilitation supervision. The orthosis is customized to the user's hand dimensions using 3D scanning technology, ensuring accurate sensor placement and adaptability to individual needs. This lightweight and flexible solution is designed for home-based rehabilitation, overcoming the limitations of traditional instrumented gloves. The paper details the design, implementation, and potential benefits of this orthosis to improve hand function evaluation recovery in patients with neurological and musculoskeletal conditions.

1 INTRODUCTION

Upper extremity motor impairments significantly impact quality of life, limiting the ability to perform daily tasks. In general, millions of people live with the effects of stroke, spinal cord injuries, cerebral palsy, and other dysfunctions affecting the hands characterized by muscle weakness and uncoordinated movements (World Health Organization, 2013; Ding et al., 2022; Feigin et al., 2022; van Eck et al., 2010; Eliasson and Gordon, 2000; McIntyre et al., 2022). These conditions place considerable demands on healthcare resources due to long-term care requirements and work absences, affecting individuals and society.

Traditional rehabilitation therapies focus on restoring motor function through repetitive exercises and therapeutic interventions. However, the patient's progress in rehabilitation is often recorded qualitatively through reports and forms, leading to subjective interpretations. In clinical practice, there is no suitable device for quantitative and dynamic measurements of hand movement. This lack of quantitative data can overlook subtle improvements, potentially discouraging continued therapy. A more objective, data-driven approach is needed to accurately measure and improve patient progress.

Wearable devices have emerged as promising tools to complement traditional therapies by enhancing movement recovery, increasing exercise frequency, and providing real-time feedback to patients and healthcare providers. For evaluation, real-time hand motion tracking presents challenges due to the numerous segments and degrees of freedom in the fingers' joints. The system must be safe, lightweight, flexible, comfortable, and designed to accommodate normal finger joint movements and hand sizes. Complex calibration should be avoided to make the system suitable for patients with severe motor impairments (Sarac et al., 2019; Buchholz and Armstrong, 1992; Bützer et al., 2021).

Although considered the gold standard for biomechanical analysis, optical tracking systems present limitations for hand motion capture due to occlusion, operational complexity, and high costs, needing to be more practical, especially outside professional laboratories. Despite advances, alternatives such as virtual reality (VR) hand pose systems still have limitations

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for quantitative evaluation applications of dynamic movement in real-time (Cejnog et al., 2021; Alnuaim et al., 2022; An et al., 2022; Gao et al., 2022). Commercially available instrumented soft gloves are mainly developed for VR gaming and gesture recognition. Although they can be used for rehabilitation, none of the current solutions provide both movement tracking and grip strength information with accuracy. Chen et al.(2021) provided a solution with both types of information; however, it is a motor glove for task-oriented rehabilitation with mirror therapy instead of providing accurate quantitative data for movement evaluation progression (Dipietro et al., 2008; Demolder et al., 2021; Henderson et al., 2021; Chen et al., 2021). In addition, soft gloves are difficult to use by people with hand motor impairments, such as spastic hands; they are not customized to individual hand sizes, which may lead to incorrect sensor positioning and incorrect measurements; they reduce the sense of touch, as well as are challenging to clean and disinfect.

The sensors commonly used in these gloves are the flex or bend sensor, which works by changing its resistance with the radius of curvature, measuring static or dynamic joint angles (Park et al., 2019; Henderson et al., 2021; Chen et al., 2021; Yang et al., 2021) and force-sensing resistors (FSRs), which work by changing its resistance as more force is applied to their surface, measuring grip strength (Park et al., 2019; Lapresa et al., 2023; Chen et al., 2021; Interlink Electronics, nd). These lightweight and low-cost sensors are adapted for different uses, allowing multiple sensor integrations.

Designing an effective evaluation system requires addressing the variability in individual hand shapes, sizes, and clinical conditions. Customizing the device for each patient ensures it fits their specific physical dimensions and accounts for muscle tone, range of motion, and skin sensitivity. This personalized approach leads to a more accurate fit, greater comfort, and enhanced functionality during rehabilitation.

For this purpose, this work presents the design of a 3D-printed instrumented hand orthosis, offering flexibility and comfort for users. The design uses a 3D scanner for customization; the orthosis uses flex sensors to monitor finger movement amplitudes and force sensors to measure grip strength. Additionally, the system includes a digital interface that enables healthcare professionals to remotely assess and track the patient's progress, allowing for continuous, data-driven adjustments to the rehabilitation plan.

2 MATERIALS AND METHODS

Integrating 3D Scanning, 3D printing, flexible materials, and advanced sensor technology results in a customized and sensor-integrated orthosis designed for hand rehabilitation. Each of the components is detailed in the following sections.

2.1 3D Scanning and Parametric Modeling

Creating a custom orthosis begins with 3D scanning technology to capture the precise user's hand shape and size. The 3D scanner offers an accuracy of 0.2mm, ensuring that the model closely mirrors the user's anatomy, providing an accurate base for further design modifications.

Once the mesh from the scan is obtained, parametric modeling is applied using DesignX® software, translating the complex mesh into a functional design. The orthosis is generated from an offset surface directly based on the precise anatomy of the user's hand.

The design focuses on simplicity and functionality. Each model incorporates internal channels for the sensor wiring and housings for both flex and force sensors, allowing all components to be integrated without affecting the orthosis's flexibility or comfort (Figure 1).

The orthosis maintains a uniform thickness of 1mm, contributing to a lightweight structure that does not limit finger movement or cause discomfort during rehabilitation.

Figure 1: 3D Model of the Hand with Orthosis Design. Author.

2.2 3D Printing Process and Material

The 3D Printing Process was based on an FDM printer, a popular additive manufacturing technique involving thermoplastic material layer-by-layer deposition.

The material used for printing the orthosis was Thermoplastic Polyurethane (TPU), chosen due to its excellent flexibility and fatigue resistance, allowing the orthosis to endure repeated movements without losing its structural integrity. This material provides a strong, supportive, lightweight structure that conforms comfortably to the user's hand without restricting motion or causing discomfort during extended wear.

Flexible spring mechanisms (Figure 2), designed to connect the orthosis components, enable movement between the phalanges without restricting mobility. These springs were printed separately and attached during the post-processing stage after completing the 3D printing.

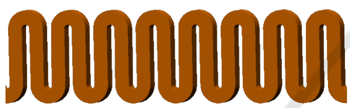

Figure 2: Flexible Spring Mechanism Designed for Joint Movement. Author.

2.3 Embedded Sensors and Signal Management

In developing the orthosis's electronic system, flex sensors and force-sensitive resistors (FSRs) were integrated to monitor finger movement and grip force. The flex sensors capture finger bending, while the FSRs measure applied force during rehabilitation exercises and grasp tasks. A current-to-voltage converter circuit was incorporated to linearize sensor response, improving the accuracy and reliability of the data. The sensors were calibrated using commercial solutions such as Biometrics® electronic goniometers and Tekscan® grip systems attached over the orthosis together with the built-in sensors.

The sensors were strategically placed to optimize data collection (Figure 3). FSRs were positioned on the distal phalanges of the index, middle, and thumb fingers for grip pressure measurement, with an additional FSR placed on the palm for overall pressure distribution. Flex sensors were placed between the metacarpals and proximal phalanges of all fingers, with additional sensors between the proximal and middle phalanges of the index, middle, and thumb for detailed tracking of joint movement.

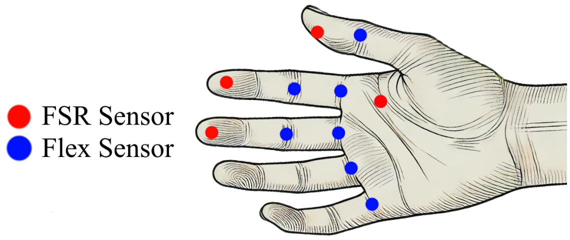

Figure 3: Positioning of Flex Sensors (blue) and FSR Sensors (red) on the Hand. Author.

The ESP32 microcontroller from Espressif was selected for its dual-core processing capabilities and integrated Wi-Fi and Bluetooth functions, which enable wireless communication between the orthosis and external devices. The ESP32, attached to the wrist or forearm, gathers sensor data, processes it, and transmits it via Bluetooth to a Python-based interface for real-time visualization. This interface allows healthcare professionals to remotely monitor the patient's progress, facilitating a data-driven rehabilitation approach by tracking changes in hand movement and grip strength over time. These components work together to deliver an accurate and reliable system for monitoring the patient's rehabilitation process.

3 RESULTS AND DISCUSSION

This section provides an overview of the design, development, and testing outcomes of the orthosis.

3.1 Design and 3D Printing Process

Figure 4 shows the final design of the printed orthosis using FDM technology with TPU material, incorporating a design choice to print the flexible spring mechanism separately to enhance its tensile strength. Printing the spring flat on the build plate increased its resistance to tension during use. Internal channels for sensor wiring were successfully integrated, providing adequate space for flex sensors without excessive pressure and ensuring accurate readings. A 1mm gap between the orthosis and the hand maintained comfort and sensor functionality. The 1mm thickness provided greater flexibility than previous 2mm prototypes, allowing for natural finger movement without compromising structural integrity. The overall use of FDM with TPU proved cost-efficient, enabling rapid prototyping, minimal material waste, and improved print quality. This resulted in a durable, flexible, and affordable orthosis suited for hand rehabilitation.

Converting the 3D mesh data from the scan posed initial challenges due to its complexity and the ab-

Figure 4: 3D Printed Orthosis with Sensors for Finger Movement and Grip Force Monitoring. Author.

sence of parametric information, making it difficult to extract precise measurements for the orthosis components. However, using DesignX® software allowed for successfully converting the scanned meshes into fully defined parametric models. This process simplified the geometry while retaining essential design features, ensuring consistency and repeatability across multiple patient-specific models.

3.2 Data Collection

The ESP32 microcontroller successfully collected data from the orthosis sensors, transmitting them via Bluetooth to the Python-based interface. The interface provided real-time sensor data visualization, allowing immediate analysis of hand movements and applied force during rehabilitation exercises. The data transmission was stable, with no significant delays, ensuring accurate monitoring during tests. However, requires improvement to enhance user experience.

The current-to-voltage conversion circuit proved effective in addressing the sensors' non-linearity. Figure 5 shows an example of the curve linearization for the FSR, with a coefficient of determination (R^2) greater than 0.98, indicating high accuracy in the force readings. Additionally, the flex sensors performed as expected, capturing detailed joint movements during various hand motions. Despite the use of commercial sensors for calibration, the process is simple and easy, allowing for dynamic calibration. The maximum error was less than 3.5% for the flex sensor in maximum flexion and for the FSR in low force levels (Figure 6). However, long-term tests are required for the maintenance and durability of the calibration, which have not yet been performed.

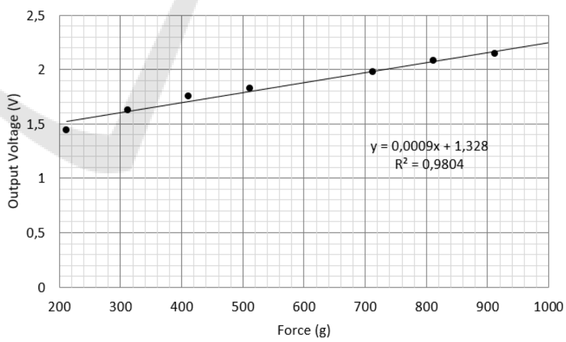

Figure 5: FSR Calibration Curve. Author.

A health volunteer performed these tests, but the design process was already performed on a patient's hand to begin the clinical and usability evaluation phase. As presented in the Introduction section, existing systems are focused on VR games, gesture recognition, or robotic rehabilitation. The lack of systems with the same purpose presented here, providing quantitative data for monitoring and evaluating hand movements, prevents further comparisons and discussions.

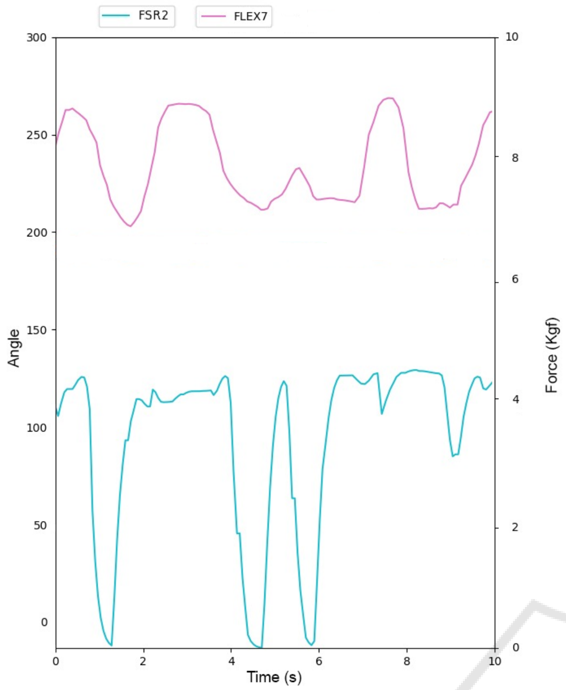

Figure 6: Real-time Force Data Visualization from FSR Sensors. Author.

4 CONCLUSIONS

This paper presented the development of a customized 3D-printed hand orthosis designed to enhance the evaluation and monitoring of hand movements in rehabilitation settings. Using 3D scanning technology and parametric modeling, we successfully created an orthosis tailored to individual hand anatomies, ensuring accurate sensor placement and user comfort. Incorporating flexible materials such as Thermoplastic Polyurethane (TPU) and flexible spring mechanisms enabled a lightweight and adaptable design that supports natural finger movements.

Embedded flex sensors and force-sensitive resistors (FSRs) provided real-time tracking of finger joint angles and grip force, respectively. Implementing a current-to-voltage conversion circuit effectively linearized the sensor outputs, and the calibration process, although using extra sensors, is simple and easy, allowing dynamic calibration to enhance the accuracy of movement and force monitoring in detailed rehabilitation tasks.

The Python-based data visualization interface, while functional, requires improvement to enhance user experience and provide more intuitive data representations for patients and healthcare professionals, enabling remote monitoring and facilitating data-driven adjustments to rehabilitation protocols.

In addition, it's a cost-effective solution that can be easily cleaned with a damp cloth, in comparison with the commercially available gloves. However, clinical trials must be performed to evaluate its effectiveness in providing accurate quantitative data and for usability.

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