1st Approach

 **Control Algorithm**:

* **Hybrid PID control system**: Used for force and position control, allowing real-time adjustments during rehabilitation.
* The control system implements both **position control** when worn by patients and **force control** when assisting grasping actions.
* Future possibilities: **Machine learning** could be integrated to adapt to individual users' progress.

 **Actuator**:

* **Soft pneumatic actuators**: For flexion and extension of fingers.
* **Flexible rotating actuators**: For abduction and adduction of fingers.

 **Response Time**:

* The experimental data showed that:
  + Finger angle can reach **90° within 0.5 seconds** with a deviation of ±2°.
  + The desired force of **0.5 N** was achieved within **1 second**, stabilizing with a bias of 6% after contact with an object.

 **Safety**:

* **Hybrid control system**: Prevents excessive force, ensuring the user is not subjected to over-exertion.
* **Soft materials** (e.g., silicone): Used to reduce injury risks compared to rigid exoskeletons.
* **Force sensors**: Monitor and prevent over-pressurization or excessive force, making the device safer for users with fragile conditions.

 **General Limitations**:

* **Durability**: Soft materials and actuators need to withstand repetitive motion, especially inflation and deflation cycles, which could limit long-term use.
* **Material nonlinearity** and **large deformation**, complicating control and response predictability.
* The efficiency of the system can decrease at higher air pressures due to energy being consumed in lateral deformation.

<https://www.mdpi.com/1424-8220/22/16/6294>

**1st Approach**

**Pros:**

* **Hybrid PID Control:** This system offers both force and position control, allowing for real-time adjustments, which is essential for rehabilitation. The possibility of integrating machine learning in the future adds potential for personalized rehabilitation.
* **Soft Pneumatic Actuators:** These actuators provide smooth, flexible movement for finger flexion and extension, which is critical for hand rehabilitation.
* **Safety Features:** The hybrid control system and force sensors ensure user safety by preventing overexertion. Soft materials like silicone reduce injury risks.
* **Quick Response Time:** The device can reach a 90° finger angle within 0.5 seconds and stabilize force application in 1 second, indicating quick responsiveness.

**Constraints:**

* **Durability Issues:** The repetitive inflation and deflation of soft materials can reduce their lifespan.
* **Nonlinear Behavior:** The soft materials have nonlinear characteristics, making it harder to predict and control the actuator’s response, particularly under large deformations.
* **Efficiency Loss at Higher Pressures:** The system consumes more energy at higher air pressures due to lateral deformations, reducing its efficiency.

2nd Approach

 **Control Algorithm**:

* **Manual control (button mode)** via a mobile app.
* **Mirror rehabilitation training mode**, which mirrors movements from the healthy hand to the impaired hand.
* **Regulated control system**: Adjusts actuator force to prevent overexertion or injury.
* **Type:** Proportional Integral Derivative (PID) control algorithm.
* **Control Frequency:** 200 Hz.
* **Model Type:** Force-position hybrid model.
* **Error Metrics:**
  + eθe\_\thetaeθ​: Error between designed and actual finger bending angle.
  + eFe\_FeF​: Error between designed contact force and actual contact force.

 **Actuator**:

* **Shape Memory Alloy (SMA) springs**: Used for extension, enabling bidirectional motion.
* Actuators are regulated for force during rehabilitation.

 **Response Time**:

* **Water-cooling system**: Prevents overheating of SMA springs and improves the actuator's response time during use.
  + Water-cooled actuator: Transition from martensite to austenite in 7.5 seconds.
  + Conventional actuator: Transition takes 16.95 seconds.

 **Safety**:

* **Water-cooling system**: Ensures safe operation by preventing the SMA springs from overheating.
* **Control system**: Prevents overexertion or injury by adjusting the force applied during rehabilitation.
* **Material Selection**: The choice of materials (e.g., Dragon Skin 30) is essential to ensure comfort and safety for user wearability.
* **Experimental Results**: No significant increase in water temperature during prolonged operation indicates good thermal management.
* **Emergency Power Off:** Power switch available on control box for patient safety.
* **Sensor Placement:** Force and position sensors sewn inside the glove to enhance safety and reliability.

 **General Limitations**:

* **Soft Actuator**: Balancing output force and bending angle due to material stiffness and dimensions.
* **SMA Spring Actuator**: Response times may not meet rehabilitation speed requirements without water cooling.
* **Cooling Structure**: Residual force affects the actuator's transparency.
* **Control Issues:** The force-position hybrid model cannot control force and position accurately simultaneously; tuning parameters are required for different operating modes.

<https://ieeexplore.ieee.org/abstract/document/10175575>

**2nd Approach**

**Pros:**

* **Manual and Mirror Mode Control:** This flexibility allows for tailored rehabilitation, with a manual mode for direct control and a mirror mode to replicate movements from the healthy hand.
* **PID Control System:** The PID control, running at 200 Hz, provides good force and position control with metrics to monitor performance.
* **SMA Actuators with Water Cooling:** Shape Memory Alloy (SMA) actuators are lightweight and compact, with water cooling improving response times significantly, from 16.95 to 7.5 seconds.
* **Safety Enhancements:** The water-cooling system prevents overheating, and safety switches allow for emergency shutoff, making the system safer for users.
* **Sensor Integration:** Sensors in the glove for force and position ensure precise control and feedback, which increases reliability.

**Constraints:**

* **SMA Response Time Without Cooling:** Without water cooling, the response time of the SMA actuators is too slow for practical rehabilitation, which could hinder performance.
* **Residual Force in Cooling Structure:** The cooling system introduces residual force, which can affect the transparency of the actuators during operation.
* **Hybrid Control Model Limitations:** The force-position hybrid model cannot perfectly control force and position simultaneously, requiring careful tuning for different scenarios.
* **Balance in Soft Actuator Design:** There's a trade-off between force output and bending angle due to material stiffness, which complicates actuator design.

3rd Approach

**Control Algorithm**

The paper does not explicitly discuss a control algorithm; it focuses primarily on the design and characterization of soft pneumatic bending actuators without detailing any specific control strategies employed.

**Actuator**

* **Type**: Soft pneumatic bending actuator
* **Materials Used**:
  + Ecoflex® 00-30 (Young Modulus: 125 kPa, Shore Hardness: 00-30)
  + Dragon Skin® 20 (Young Modulus: 1.11 MPa, Shore Hardness: A-20)
* **Mechanism**: The actuator functions through inflation of embedded air chambers, which causes bending movement. A strain-limiting fabric is used to control strain during actuation.

**General Limitations**

* **Force Output**: The soft actuators produce limited force, which may not be sufficient to actuate stiffer joints, such as the metacarpo-phalangeal (MCP) joint.
* **Customizability**: High customizability is required due to the varying geometry and stiffness of patients' hands, which complicates the design.

**Response Time**

The paper discusses the step response of the bending actuator, indicating that it responds quickly initially but then reaches a steady state where further increases in input pressure yield diminishing returns in response.

**Safety**

The inherent compliance of soft actuators is noted as beneficial for biomedical applications, as it ensures a safer interaction with human body parts, minimizing the risk of injury during rehabilitation.

Design and Characterization of Soft Actuator for Hand Rehabilitation Application

**3rd Approach**

**Pros:**

* **Soft Pneumatic Bending Actuators:** These actuators are highly compliant, making them safer for interactions with the human body, especially in rehabilitation applications.
* **Material Selection:** The use of soft materials like Ecoflex® and Dragon Skin® allows for comfortable and flexible rehabilitation devices.
* **Strain-Limiting Mechanism:** The inclusion of strain-limiting fabric helps control the amount of strain during actuation, ensuring safer, more predictable movements.
* **Quick Initial Response:** The actuator exhibits a quick initial response, which can be beneficial for rehabilitation exercises requiring rapid movements.

**Constraints:**

* **Limited Force Output:** The soft actuators may not provide enough force to move stiffer joints like the MCP joint, limiting their use in more demanding rehabilitation tasks.
* **Customizability Requirements:** Due to variations in hand geometry and stiffness, the device needs to be highly customizable, which complicates the design and manufacturing process.
* **Diminishing Response:** While the actuator has a quick initial response, further increases in pressure yield diminishing returns, limiting its effectiveness for more intensive rehabilitation exercises.