Article Summary
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This article presents the design, control architecture, and clinical evaluation of the National Taiwan University Hospital-ARM (NTUH-ARM), a seven-degree-of-freedom (DOF) upper-limb rehabilitation exoskeleton developed for stroke therapy. The work integrates advanced kinematic modeling, force and torque sensing, and patient-cooperative impedance control strategies to support patient recovery across passive, active, and assist-as-needed (AAN) rehabilitation modes.

The research stems from the growing need for effective robot-assisted rehabilitation after strokes, since it is a condition that frequently causes motor impairment and partial or total loss of arm function. Robotic rehabilitation offers higher training intensity to patients, reduces the clinician's workload, and provides measurable performance feedback that can be used to accelerate recovery time. Unlike end-effector devices typically used, the NTUH-ARM employs an exoskeleton structure that better aligns with human joints, allowing for more accurate control of individual joint angles and providing a larger range of motion.

The NTUH-ARM's mechanical design includes seven DOFs, five for the shoulder and one for each elbow flexion and prismatic translation. This redundancy in actuation allows the robot to avoid kinematic singularities during path planning and accommodates natural shoulder movement, adapting to the variations in human anatomy. Two six-axis force-torque sensors, mounted near the upper arm and wrist, provide real-time measurements of interaction forces, enabling individualized torque estimation and patient-specific assistance.

To interface the robot with the actual human arm, the system uses a detailed kinematic mapping between robot joints and the human's shoulder and elbow DOFs. A human-arm dynamic model was developed using Lagrangian mechanics to incorporate inertia, Coriolis, gravity, and friction components. Using force-torque sensor data and a gravity compensation algorithm, the robot estimates patient-generated torque and uses it as the primary input for control.

A unique contribution of this work is the AAN strategy, which assists only when the patient falls behind a predefined motion path. Using cubic spline interpolation, therapists create smooth desired motion profiles for joint angles, velocities, and acceleration. The controller then compares real-time joint motion with the defined trajectory and applies assistive torque only when the patient is unable to maintain the pace. A switching mechanism also determines whether the robot operates in passive, active, or assistive mode based on the measured torques and trajectory errors. Lyapunov stability analysis demonstrated that the control laws guaranteed convergence of joint angles and angular velocities, ensuring safe and stable operation.

The authors validated the system through clinical trials with six stroke patients over twelve sessions. In passive mode, the NTUH-ARM exhibited accurate trajectory tracking with low RMS error. In the active and assistive modes, results from a “window-cleaning” game showed that the assistive mode enabled patients to achieve similar motion patterns with significantly lower exerted torque, confirming the robot’s ability to reduce physical load as needed. Measures such as Fugl-Meyer scores, joint torque profiles, and frequency-domain smoothness analyses demonstrated improvements in motor control, especially among more acute stroke patients.

Overall, the study presented a robust patient-cooperative control system that combined human arm modeling, sensor-based torque estimation, and adaptive assistance. Clinical results suggest that the NTUH-ARM with AAN control is an effective tool for upper-limb stroke rehabilitation.