Neurobypass 1.0: A Mechanical Approach on 3D-Printed Neurocontrolled Hand Orthosis for Subacute Post-Stroke Rehabilitation

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Abstract:

Stroke is one of the leading causes of motor disability worldwide, directly impairing limb functionality and compromising individuals' independence in daily activities. Stroke-induced hand paresis requires assistive devices whose kinematics, compliance, and morphology faithfully emulate healthy biomechanics. Neurobypass 1.0, under SENAI CIMATEC's ReaPTA 5.0 programme, delivers a patient-personalized hand orthosis neuro-controlled by EEG that is engineered around three mechanical pillars: biomimicry, human-like motion and additive manufacturing. The technology integrates electroencephalography (EEG) to command robotic elements via recognition of neural motor-intention patterns, additive manufacturing with flexible and rigid materials (TPU/PLA) and an immersive virtual-reality environment, delivering neurofeedback that stimulates neuroplasticity. By fusing brain-computer-interface (BCI), multi-material 3D printing, modular biomimetic geometry and minimum jerk kinematics into a single, low-cost platform tht amplifies the therapeutic impact alongside conventional therapy, providing clinicians with an evidence-driven, easily serviceable device to accelerate upper-limb functional recovery in post-stroke patients.

Keywords: Brain-computer interface. Stroke rehabilitation. Hand exoskeleton. Motor imagery. Additive manufacturing, Motor Imagery, Neuroplasticity, Robot-assisted therapy, OpenBCI.

Abbreviations: EEG, electroencephalography. BCI, brain-computer interface. ROM, range of motion. PLA, polylactic acid. TPU, thermoplastic polyurethane. MCP, metacarpophalangeal. MVC, maximal voluntary contraction. DCL, dynamic control law. VR, virtual reality.

1. Introduction

Stroke is one of the leading causes of motor disabilities worldwide, significantly compromising upper limb function and individuals' independence in daily activities [1]. Hand paresis represents a recurrent and difficult-to-rehabilitate condition, requiring therapeutic approaches that integrate biomechanics, neurophysiology, and sensorimotor factors to the functional recovery process [1][2][3].

Over the past decades, advances in brain-computer interfaces and motor imagery techniques combined with sensory feedback have considerably expanded the potential of assistive technologies for post-stroke rehabilitation. Rehabilitation systems that incorporate recognition of motor intention via electroencephalography, robotic devices and immersive environments have proven effectiveness in modulating neuroplasticity into recovering residual corticospinal pathways, promoting adaptive functional neuro reorganization [4][5][6].

There is consistent evidence that task-oriented training strategies, when integrated with wearable sensors and robotic systems, contribute to improve motor accuracy and functional performance, while chronic patients may not experience such benefits, sub-acute patients do benefit from exoskeletal gait training alongside traditional therapy [3][7].

Within this context, the present work aims to present the development and technological basis of the "**Neurobypass 1.0**" a neuro-controlled robotic hand orthosis, through additive manufacturing and OpenBCI platform. It seeks to deliver an accessible, personalized, biomimetic, and clinically replicable solution for upper limb rehabilitation in the subacute phase of stroke, aligned with scientific evidence and normative guidelines [2][8][9].

2. Methodology

This study begins with a State-of-the-Art review about rehabilitation orthosis. Grounded in multidisciplinary integration between engineering and clinical rehabilitation. The methodological configuration aligns with scientific practices in **Germany**, **China** and the **United States of America** [9][10][11].

Figure 1. Exoskeleton for Rehabilitation.

Source: Wege A, et al [10].

References were selected from indexed databases such as PubMed, Scopus, IEEE Xplore and Web of Science, ensuring scientific relevance and reliability, by using keywords such as Brain-computer interface, Motor Imagery, Stroke rehabilitation, Neuroplasticity, Robot-assisted therapy and OpenBCI.

Figure 2. 3D Printed Prosthetics for Kids.

Source: Grundmandis [12].

The selected literatures address neuroplasticity, brain computer interfaces, additive manufacturing, and biomechanical modelling of artificial limbs for rehabilitation [1][13][14]. Clinical and ergonomic aspects were extracted from experimental research and articles on post-stroke motor recovery, particularly concerning motor imagery training, corticospinal reorganization, and assistive robotics [6][7]. Engineering aspects such as material selection, mechanical properties, and validation procedures followed technical norms and consolidated protocols in biomechanical testing [2][9][15].

2.1. Global Function

The global function of the system was defined as the execution of opening and closing the affected hand using robotic assistance and motor intention recognition of patients with post-stroke hand paresis (within the sub-acute period). The device acts as mediator between neural movement intention (decoded via EEG and machine learning) and the movement itself of the affected hand [3][4].

To increase adaptability and prosthetic embodiment, the design complies with biomechanical limitations, user comfort (ergonomics) and human-like controlled movement. This goal aligns with evidence indicating that assistive devices integrated with brain–computer interfaces enhance motor recovery when combined conventional therapy and motor imagery recognition and sensory feedback within virtual environments [5][6].

2.2. Functional Synthesis

The functional synthesis of the **Neurobypass 1.0** exoskeleton focuses on the integration of biomechanics, ergonomics and neuro-assisted control.

The system's functional breakdown resulted in four main sub-functions:

(I) Ergonomic fixation of the orthosis to the upper limb.

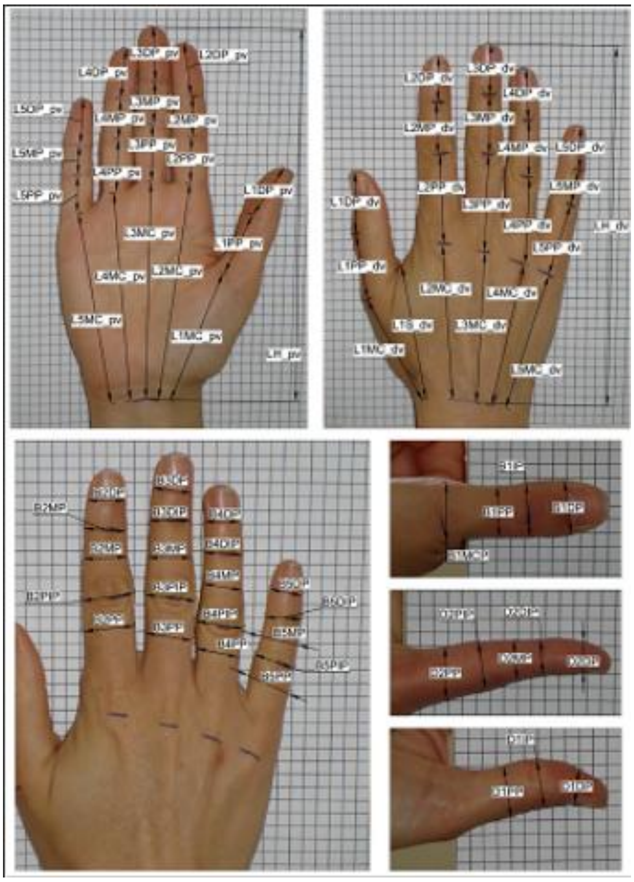
(II) Passive-assisted articulation of the fingers.

(III) Mechanical transmission of controlled flexion movement.

(IV) Neuro-assisted triggering via cortical signals.

The synthesis process was guided by Spanish anthropometric data and ergonomic requirements of comfort, safety, and structural lightness[2][16][17].

Figure 3. Hand Measurements.



Source: Vergara, et al. [16].

2.3. Concept Generation

The concept generation phase included selection criteria such as structural modularity, biomimicry, adaptable anthropometry, low weight and cost, selective rigidity, and compatibility with 3D printing for personalization [9][16][17].

These concepts were selected to ensure compatibility with real clinical application, optimizing reproducibility, ergonomics, and safe integration with neuro-controlled systems, thus validating the technical foundations for future development stages [14].

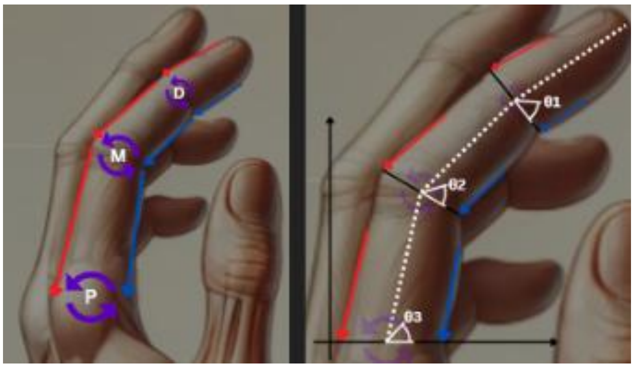
2.4. Morphological Matrix

In the conceptual mechanics stage of the project, the Morphological Matrix was developed to support the dimensional and functional parameters necessary for the biomechanical modelling of a hand exoskeleton.

The selected parameters include muscle force, joint torque, moment of inertia, angular velocity (ω), angular acceleration (α), friction coefficients, joint range of motion (ROM), and movement trajectory.

The architecture shown on **Figure 4** aims to ensure the precise transmission of forces from the motor actuators by artificial tendons, allowing the execution of movements compatible with human physiology.

Figure 4. Illustration of Forces and Moments.



Source: Authorial.

The muscle force capacity of the intrinsic and extrinsic muscles of the hand was defined based on anatomical and physiological data. The force required to simulate intrinsic muscles varies (About **300 N** in the flexors and **150 N** in the extensors, for fingers phalanges) depending on the muscle group involved, the velocity and its length [9][14].

Joint torque, derived from the product of muscle force and lever arm, was determined using biomechanical models. Upper limb simulations show that torque at the metacarpophalangeal (MCP) joints typically ranges from 0.5 to 2.5 Nm, in functional tasks [2].

Regarding moment of inertia, inertial characteristics of robotic anthropomorphic fingers estimate finger segment inertia between **0.003** and **0.02 kg·m²**, which is critical for modelling dynamics and control [9][18].

For the angular velocity (ω) and angular acceleration (α) parameters, finite element analyses of portable exoskeletons identify typical angular velocities for finger flexion between **150–250°/s** and angular accelerations up to **1000°/s²** during high-speed movement. The coefficient of friction between finger-pad and contact surfaces was assumed to vary between **0.45** and **0.85**, depending on surface texture and moisture, directly impacting grip force and precision [18][19].

The joint range of motion followed anthropometric data from literature and medical standards, with flexion/extension amplitudes in MCP joints between **0°** and **90°**, and in interphalangeal joints between **0°** and **120°** [14].

Finally, the trajectory of movement was based on planar and three-dimensional models simulating natural kinematics during prehension, enabling the refinement of control parameters and the selection of actuation components compatible with the neuromechanical objectives of the project [11].

2.5. Biomimicry Movement Control

To ensure physiologically human-like movements, for rehabilitation, this study adopts a control model based on the minimization of jerk (the third derivative of position) [20]. This approach defines that the central nervous system plans voluntary motion by minimizing abrupt acceleration variations, resulting in smoother and more efficient trajectories. This is mathematically formalized through a cost function that penalizes excessive jerk fluctuations, expressed as:

$$J = \int_0^T \sum_{i=1}^{n} \left(\frac{d^3 x_i}{dt^3}\right)^2 d_t \quad (1)$$

This model provides optimal multi-dimensional motion planning by reducing oscillations and improving control in robotic-assisted motor tasks.

2.5.1. Position Equation

Considering boundary conditions with defined initial/final positions and zero velocity and acceleration, the ideal displacement trajectory over time is expressed as:

$$x(t) = D * [6 * \left(\frac{t}{T_f}\right)^5 - 15 * \left(\frac{t}{T_f}\right)^4 + 10 * \left(\frac{t}{T_f}\right)^3] \quad (2)$$

2.5.2. Velocity Equation

The first derivative of the position yields a smooth, bell-shaped velocity profile, characteristic of natural reaching movements:

$$v(t) = D * [30 * \left(\frac{t}{T_f}\right)^4 - 60 * \left(\frac{t}{T_f}\right)^3 + 30 * \left(\frac{t}{T_f}\right)^2] \quad (3)$$

2.5.3. Acceleration Equation

The acceleration profile indicates a gradual speed-up and slow-down pattern, minimizing mechanical shocks and maximizing ergonomic comfort:

$$a(t) = \frac{D}{T_f} * [120 * \left(\frac{t}{T_f}\right)^3 - 180 * \left(\frac{t}{T_f}\right)^2 + 60 * \left(\frac{t}{T_f}\right)] \quad (4)$$

2.5.4. Optimal Duration Equation

The optimal time required for voluntary motion does not scale linearly with distance. Instead, it follows a sublinear cubic relationship defined by:

$$T_f = K * \sqrt[3]{D} \quad (5)$$

This reflects an efficient motor planning strategy from a neuromechanical perspective.

Incorporating the minimum-jerk model into the Neurobypass 1.0 hand exoskeleton provides a robust mathematical foundation for trajectory generation, allowing for realistic and safe EEG-driven motor assistance.

This approach, coupled with multisensory feedback, promotes cortical reorganization and improves rehabilitation outcomes for post-stroke patients [1][3][5].

2.6. Technological Risk Analysis

The primary technological risk identified in the project concerns the potential for self-injury resulting from misalignment between cortical commands and robotic actuation. Since users present with reduced or absent voluntary motor control, the system must strictly respect kinematic and kinetic limits of the hand and forearm during assisted motion.

To mitigate this risk, the exoskeleton was designed with compliance mechanisms and actuation constraints that limit angular excursion to physiological ranges of motion, based on anatomical models and musculoskeletal simulations [2][9][11].

Joint torque is regulated within the safe biomechanical thresholds observed in post-stroke conditions, accounting for changes in tissue resistance and muscular tone [14][21].

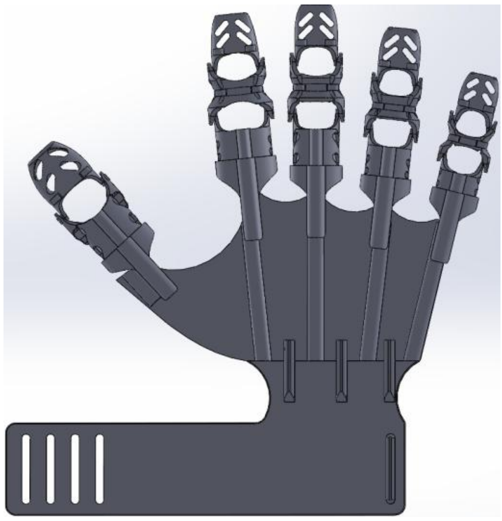
Additionally, real-time feedback from the virtual environment and electroencephalographic command analysis provides dynamic control, allowing the system to adjust motion intensity in response to the user's cortical activation level. This neuro-adaptive mechanism ensures that no movement is executed without neural intention, significantly reducing the probability of mechanical overcompensation [3][4].

The exoskeleton structure and materials also follow ergonomic principles to avoid pressure peaks on sensitive regions. Finger articulation components were dimensioned to allow sufficient stiffness for controlled motion while preserving flexibility to absorb impact and misalignment, aiming to reproduce only physiologically safe trajectories. These solutions are aligned with the anthropometric and ergonomic parameters described in the technical literature, with emphasis on modularity, compliance, and soft tissue adaptation [2][10].

3. Results And Discussion

The technical development phase of the *"Neurobypass 1.0"* is currently at the stage of prototyping, functional validation and optimization. The methodological strategy was guided by principles of personalized assistive engineering, ensuring coherence between biomechanical performance, technological feasibility, and clinical applicability.

Figure 5. "Neurobypass" 1.0 Prototype.



Source: Authorial.

The results obtained so far consolidate the system as a low-cost, 3D-printed, neuro-assisted hand exoskeleton with biomimetic architecture and EEG-based control integration. Initial calculations validate the mechanical transmission based on additive manufacturing using **PLA** and **TPU**, achieving required balance between structural rigidity and compliant deformation for safe finger actuation. The articulation profile followed the motion curves derived from the minimum-jerk model, confirming compatibility with natural grasping dynamics [20].

The control architecture, developed on the OpenBCI platform, successfully recognizing motor imagery patterns, for subacute post-stroke profiles, provide consistent actuation triggers in control test scenarios. This integration aligns with evidence on the efficacy of EEG-based BCI for promoting corticospinal reorganization and functional gains [4][5][22].

Furthermore, anthropometric and ergonomic validation confirms optimal fit and comfort, complying with dorsal and palmar geometries of the upper limb for personalized adaptation [16].

From a clinical standpoint, the current configuration addresses fundamental safety concerns regarding torque, angular velocity and joint range of motion, remaining within biomechanical thresholds for subacute rehabilitation [2][9][11][14].

These results position the system as a viable, replicable solution for application in real clinical environments, contributing to an innovative, neurointeractive rehabilitation framework grounded in low-cost technologies and functional neuroplasticity.

4. Conclusion

The development of the *"**Neurobypass 1.0**"* system resulted in a personalized, low-cost, EEG-driven hand exoskeleton that integrates biomimetic mechanics, additive manufacturing, and neuroadaptive control. Structural tests confirmed that the **TPU/PLA** transmission system delivers compliant yet safe finger actuation, following movement trajectories predicted by the minimum-jerk model [20][21]. Anthropometric validation ensured ergonomic adherence, while mechanical parameters such as torque and range of motion remained within safe biomechanical thresholds for subacute rehabilitation [2][9][16].

These findings establish **Neurobypass 1.0** as a replicable, clinically feasible assistive device, advancing the field of neurointeractive rehabilitation through robust, evidence-based engineering and physiological modelling [3].

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