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20th EDITION

REHABILITATION
Yesterday – Today – Tomorrow
Syracuse 16 – 19 October 2025

Cutting edge research in Artificial Hands Area

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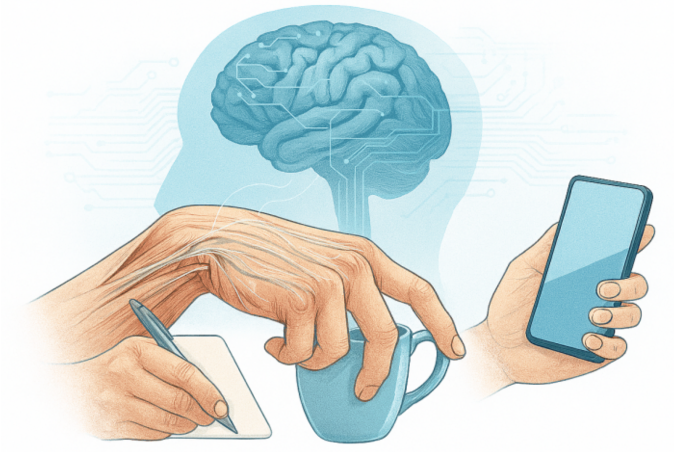
The role of the hand in functional independence and self-perception

“Impaired motor functions after stroke are common and negatively affect patients’ activities of daily living and quality of life. In particular, hand motor function…often returns slowly and incompletely after stroke.”

Ingwersen et al., Neurol Res Pract., 2021



“Upper limb amputations cause numerous physical and psychosocial challenges including disruptions to quality of life as well as limitations in participation in society.”

Ghorbani et al., Int. J. Orthop. Trauma Nurs., 2020

Upper limb prosthetics

Key aspects

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- **Current challenges** — High functional complexity + aesthetic component
- **Types of prostheses** — Cosmetics, passive, active
- **Components** — Functional hand, joints, custom socket
- **Myoelectric control** — Based on isometric contraction of residual muscles
- **Future technologies** — BCI, direct neural control

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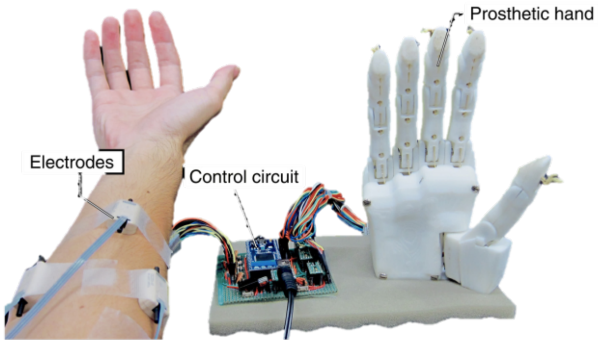
Evolution of hand prostheses



2020s – Smart Bionics

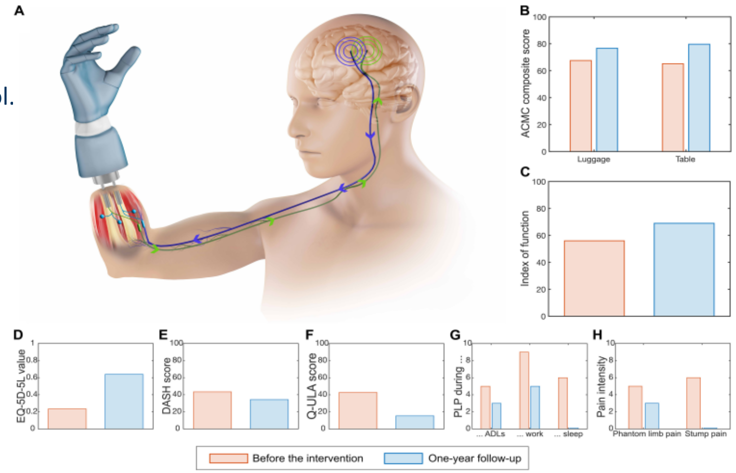
Advanced systems integrating neural interfaces, sensory feedback, and AI for intuitive, embodied control.
(Nature, IEEE, PubMed)

2007 – i-Limb Hand

First commercially available bionic hand with individually motorized fingers and multiple grip patterns. (Touch Bionics, IEEE)

1958–1964 – Myoelectric Era Begins

EMG-controlled prostheses developed in the USSR and later commercialized, marking the birth of active control.
(eprints.soton.ac.uk)



Ortiz-Catalan et al., Science Robotics, 2023

1520 – Götz von Berlichingen

Mechanical articulated hand enabling basic grip — a pioneering example of upper limb restoration.
(Historical records)

ca. 3000 BCE – Ancient Egypt

First known prosthesis: a functional toe, highlighting early needs for limb replacement.
(British Museum, J. of Egyptian Archaeology)

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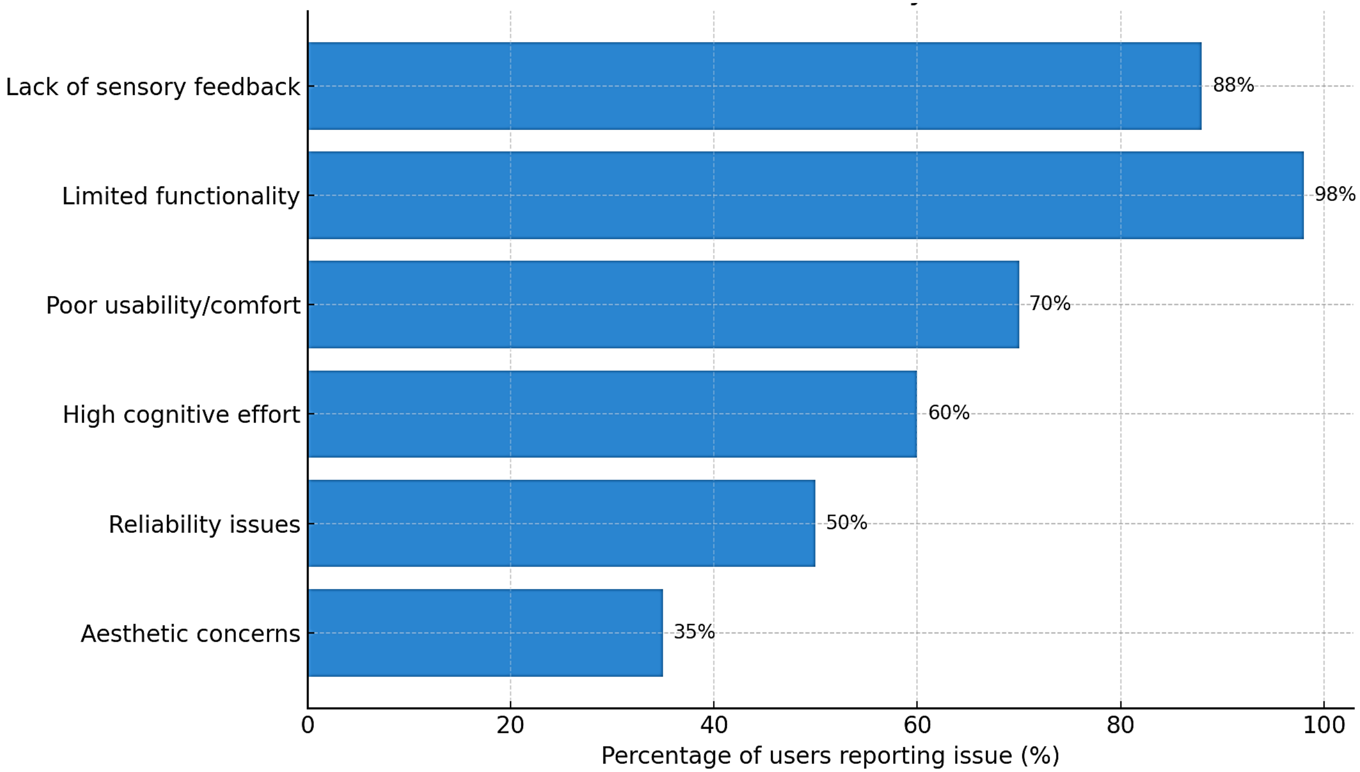
Why do users abandon myoelectric prostheses?

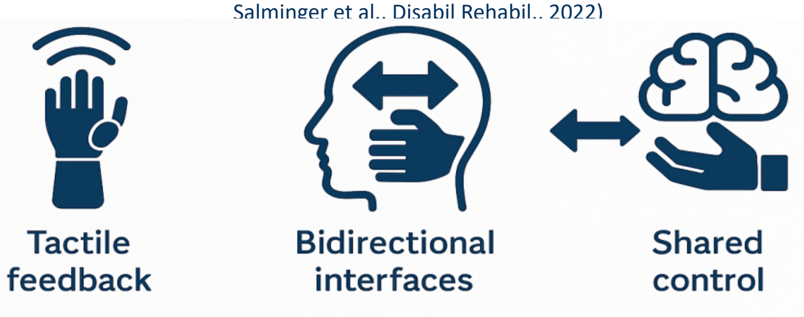
Despite technological advances, up to 50% of users abandon myoelectric prostheses due to key limitations, including poor functionality, unintuitive control, and—most critically—the absence of sensory feedback, which 85–88% of users identify as essential.

The lack of automatic sensory input imposes a significant visual and cognitive load.

Recent studies show that implementing tactile or bidirectional feedback, combined with shared control strategies, significantly enhances grasp performance and reduces mental effort.

(Wells et al., Sensors, 2022., Jabban et al., JNER, 2022; Salminger et al., Disabil Rehabil., 2022)



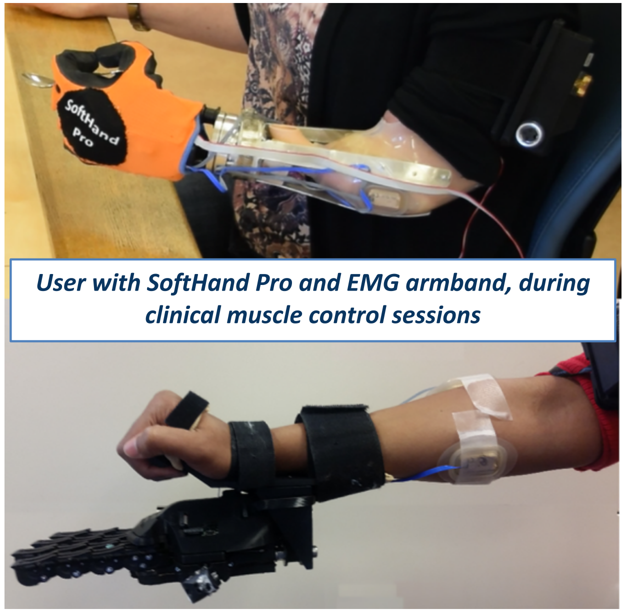


Tactile feedback, bidirectional interfaces, and shared control strategies improve task precision, enhance embodiment, and reduce cognitive effort.

Enabling lightweight and adaptive prosthetic designs

Miniaturized, tendon-driven or pneumatic actuators enable lighter prostheses and reduce user fatigue. ***Soft robotic hands*** improve passive compliance and accommodate a wider variety of grasp shapes.

As highlighted in the soft robotics literature*, miniaturized and compliant actuation enables lighter and more adaptive prosthetic hands, improving user comfort, reach, and daily usability.



User with SoftHand Pro and EMG armband, during clinical muscle control sessions

Clinical impact:
- improved wearability;
- higher user satisfaction;
- better cosmetic and functional acceptance.

SoftHand Pro prosthesis with cosmetic glove

*Catalano et al., Bioinspir. Biomim. 2014.
*Ciullo et al., Front. Robot. AI, 2021
*Bicchi et al., Nat. Mater., 2011

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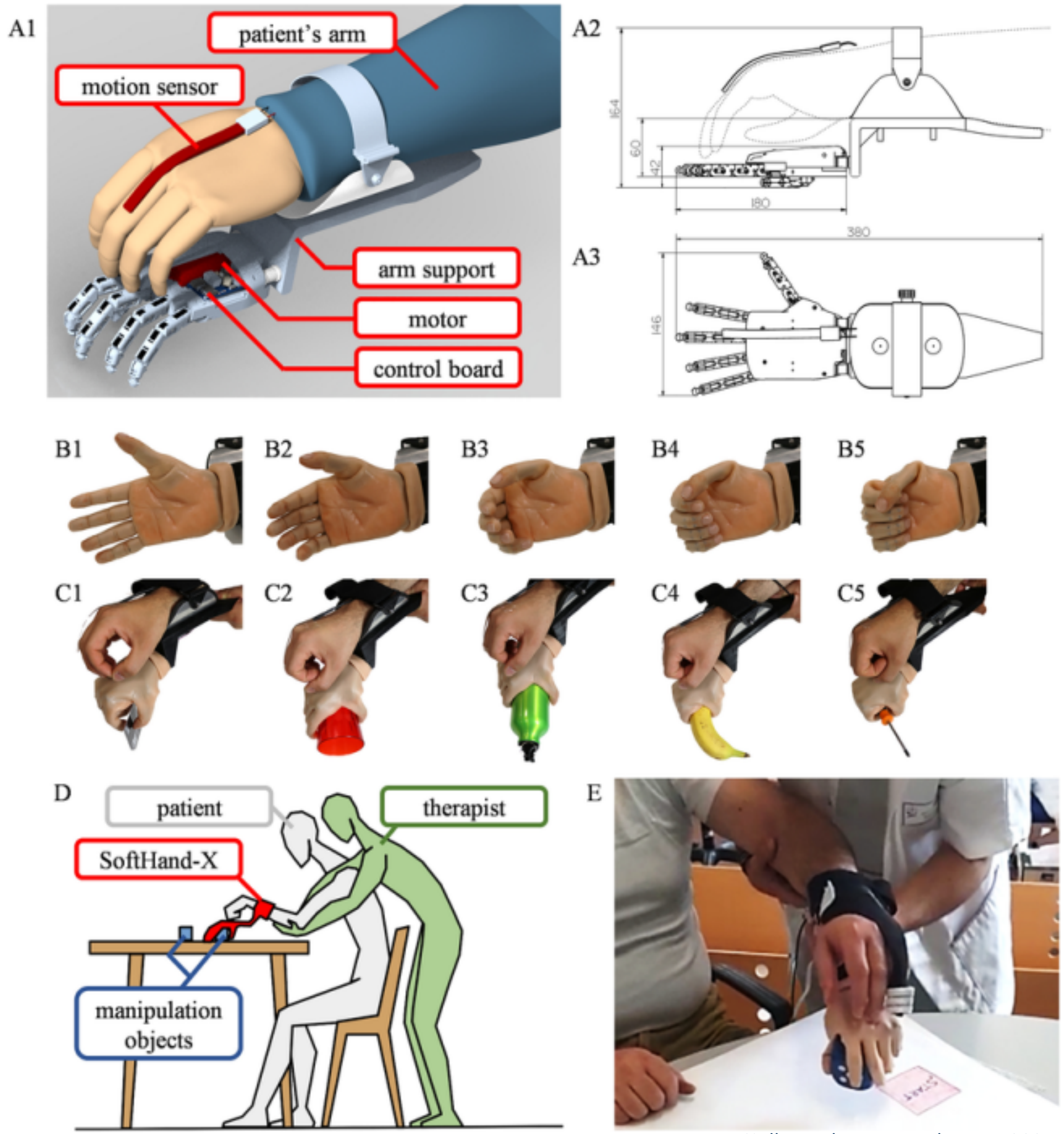
Enabling lightweight and adaptive prosthetic designs

A1-A2-A3: hardware components with graphical representation of the system and project drawing.

B1-B2-B3-B4-B5: frames of different hand configurations, from open to closed hand positions, representing the different phases of robotic grasping.

C1-C2-C3-C4-C5: functional grasping of daily-life objects of various shapes.

D-E rehabilitation setup. The subject uses the SoftHand-X to manipulate objects, while the therapist observes and supervises the exercise.



Ciullo et al., Front. Robot. AI, 2021

Rehabilitation setup with SoftHand-X

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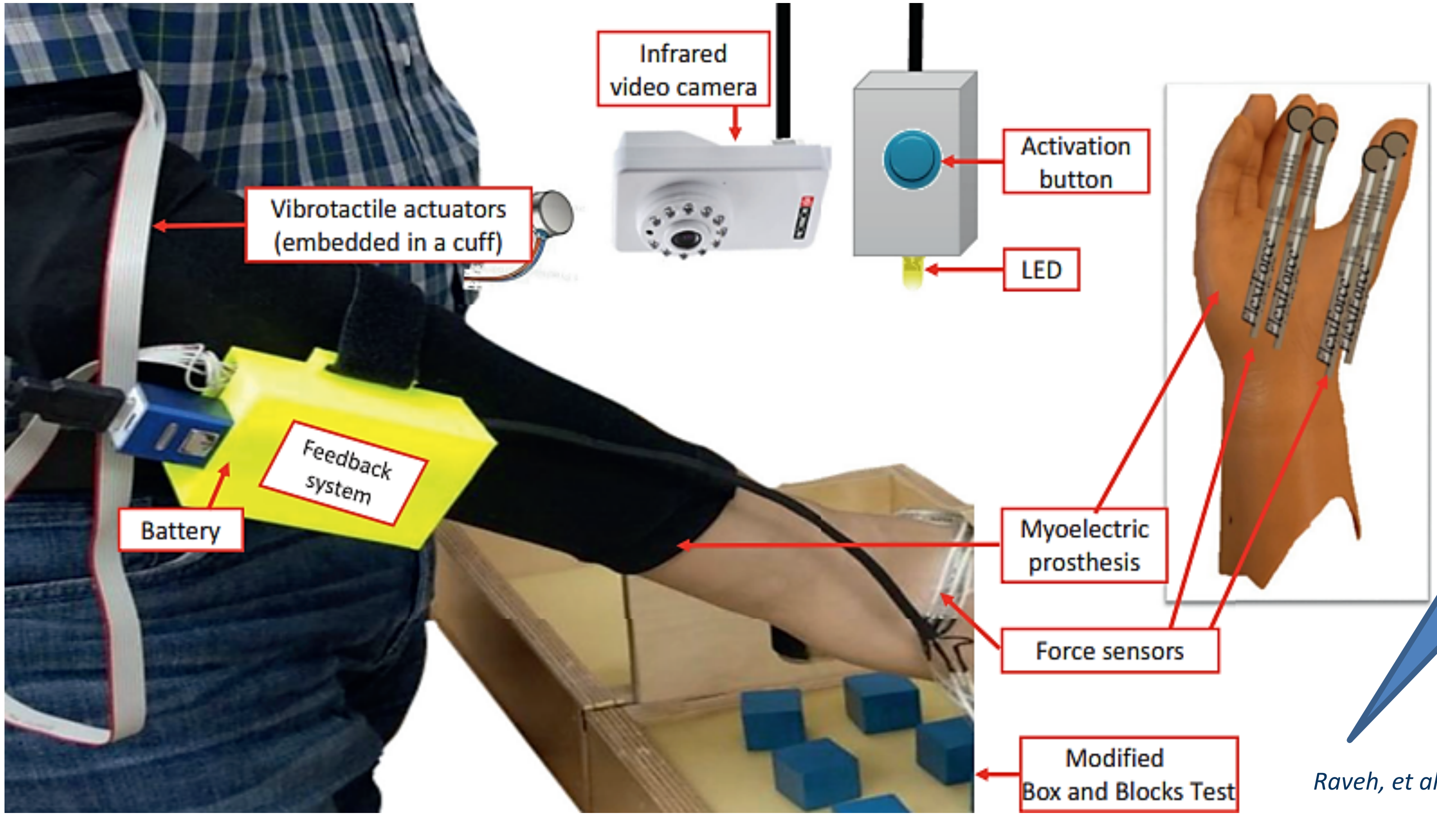
A case report: Enhancing grasp control through tactile sensation

Continuous tactile feedback improves grip precision, especially in unstructured or dynamic tasks.

<u>Clinical impact:</u>

- Reduced fall rate;
- increased safety during fine motor tasks (e.g., picking up fragile objects, tying shoelaces).



Experimental setup

Raveh, et al., Archives of Physical Medicine and Rehabilitation, 2018.

A case report:
Enhancing grasp control through tactile sensation

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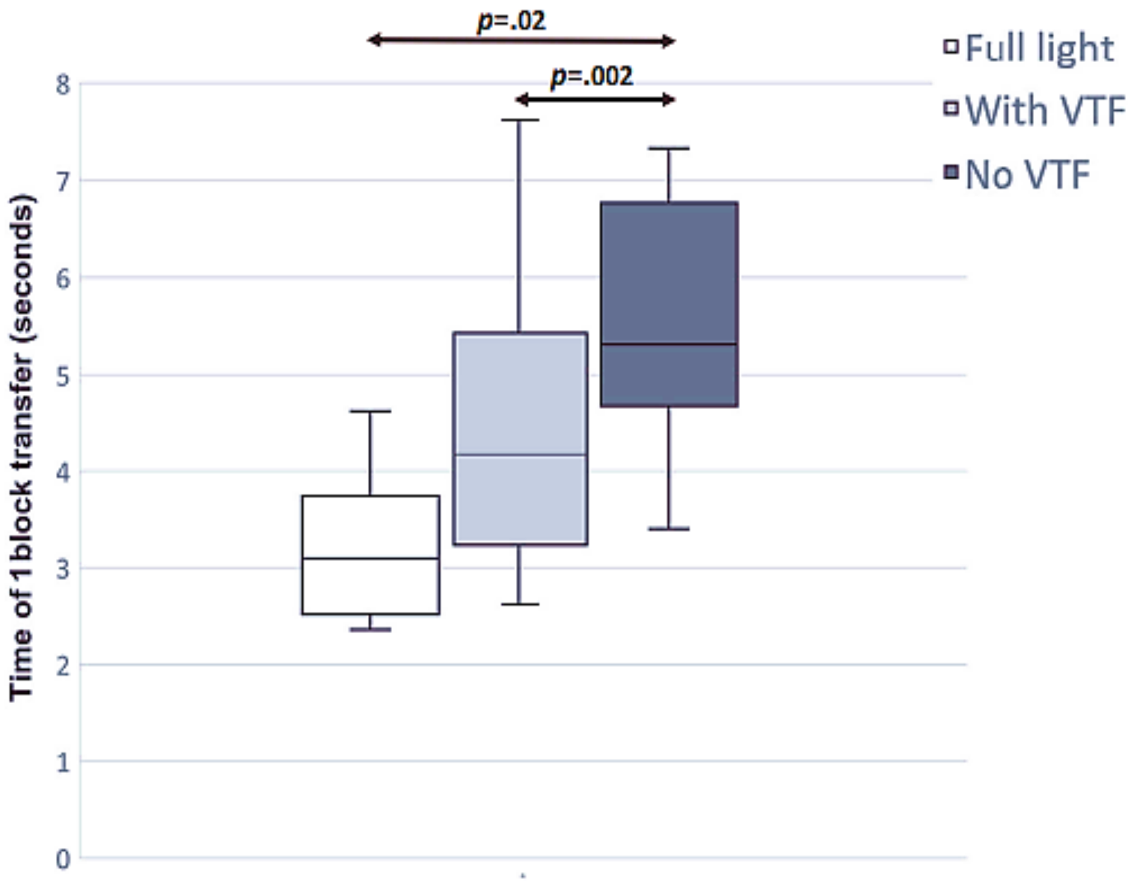
Restoring continuous tactile feedback significantly improves grasp security in delicate tasks.

In transradial amputees, adding vibrotactile feedback during functional tests like the **Box and Blocks Test** reduced drop errors (4.5 vs 2.0) and empty grasps (6.5 vs 3.0), compared to control conditions under visual limitation.

The boxplots show that ***block transfer time*** was shortest under full light conditions, increased with **visual-tactile feedback (VTF),** and was longest without VTF.

Statistical analysis revealed significant differences between full light and both VTF (p = .02) and no VTF (p = .002) conditions.



Raveh, et al., Archives of Physical Medicine and Rehabilitation, 2018.

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From cortical motor input to prosthetic movement, regulated by residual muscle activation and sensory feedback:

scientific reports

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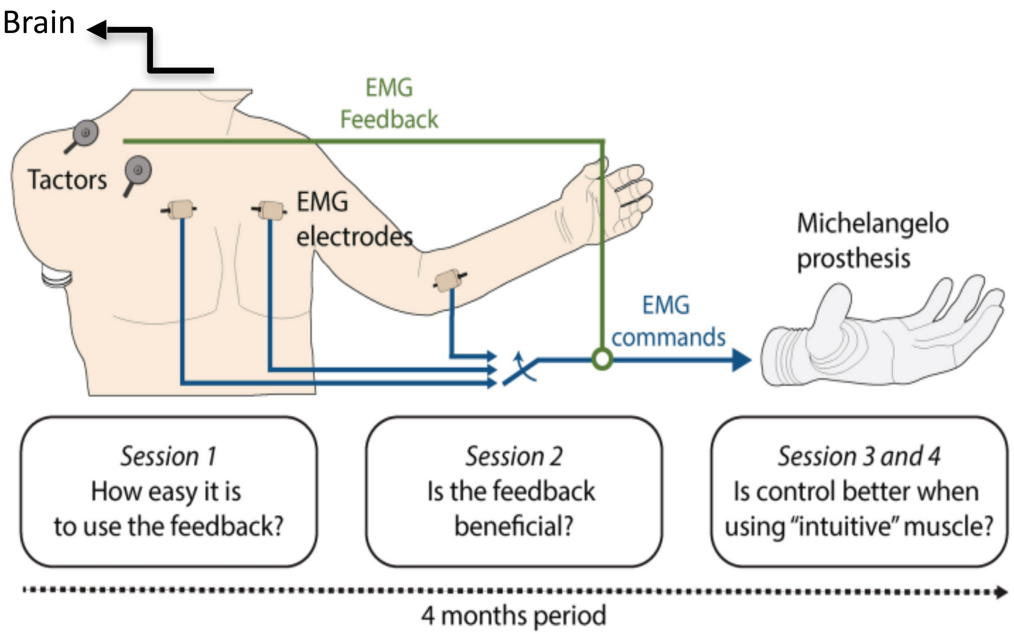
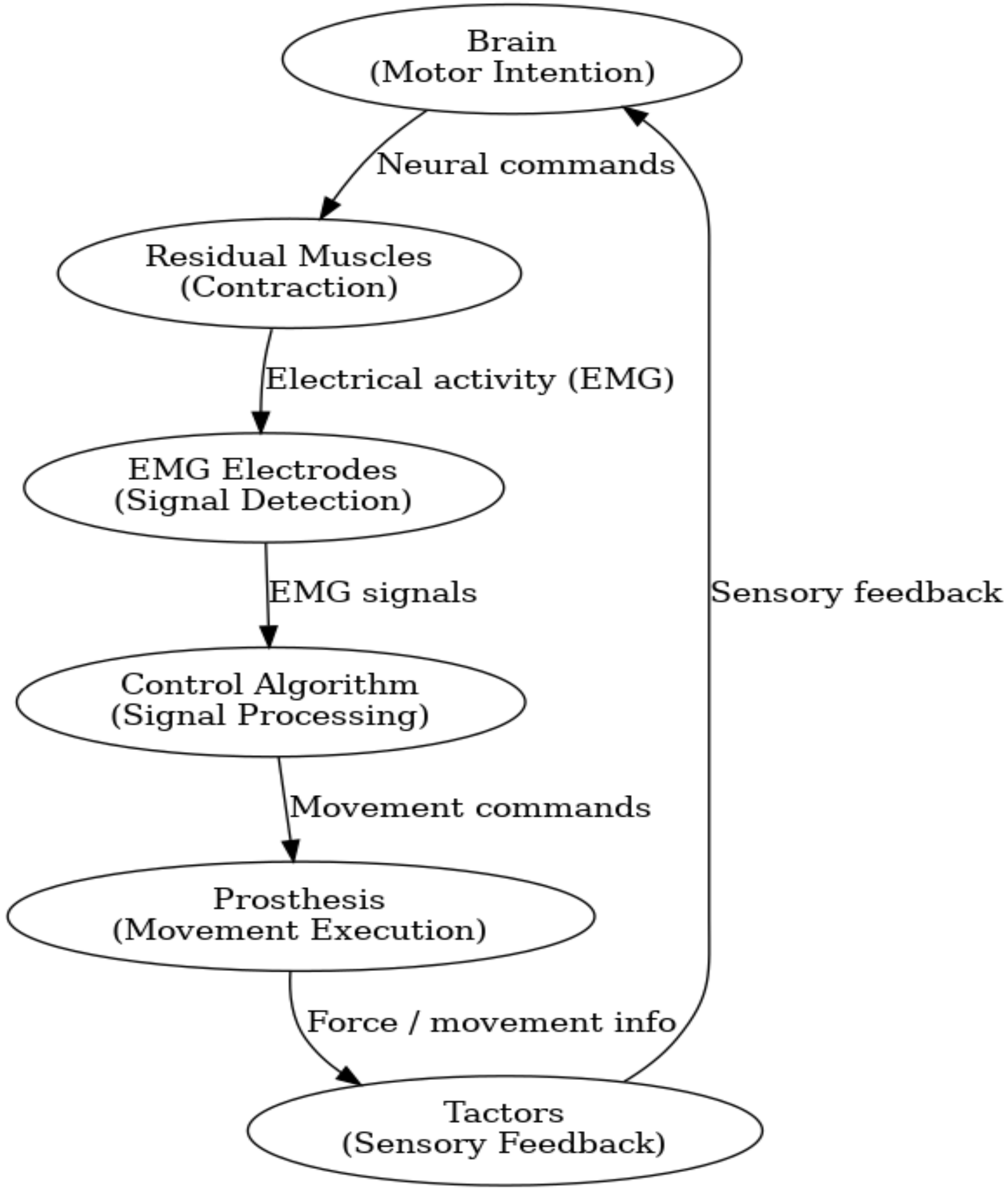
Application of EMG feedback for hand prosthesis control in high-level amputation: a case study

Jack Tchimino[1], Rehne Lessmann Hansen[2], Peter Holmberg Jørgensen[2], Jakob Dideriksen[1] & Strahinja Dosen[1]





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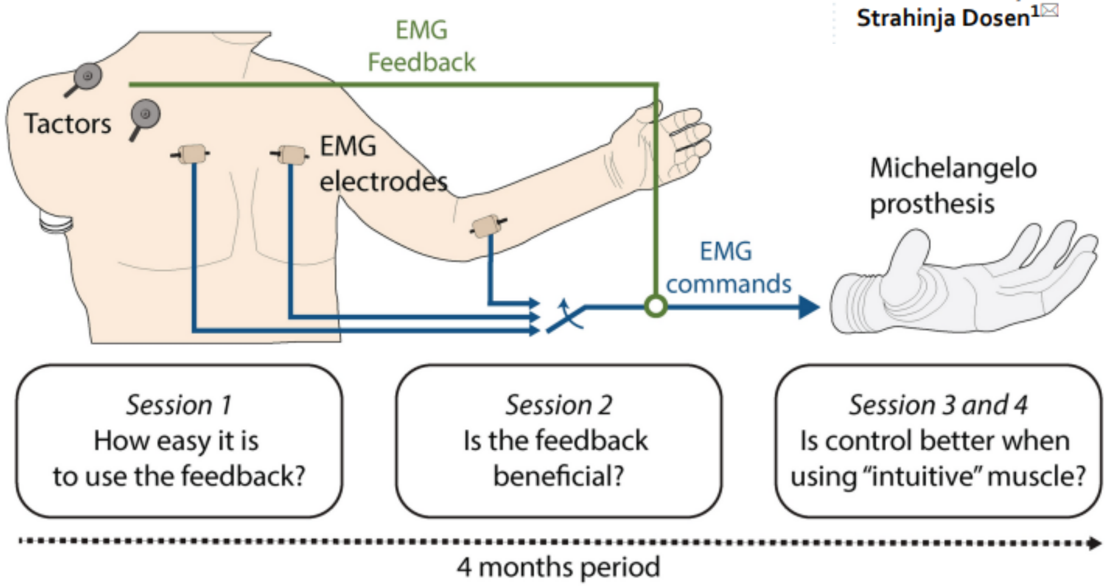

Objective: To assess the effectiveness of an EMG-based vibrotactile feedback system for strength control training in a patient with transhumeral amputation and osseointegrated implant, in the pre-prosthetic phase.

Methods:

- Participant: Male, 54 years old, right arm amputation, without a definitive prosthesis.
- Control interface: EMG signals from the pectoralis major muscle.
- Feedback: Vibrotactile stimulation on the shoulder proportional to the level of muscle activation.
- Task: Regulate grip strength according to visual targets, in 4 sessions over 4 months.

Tchimino et al., Scientific reports/Nature, 2024

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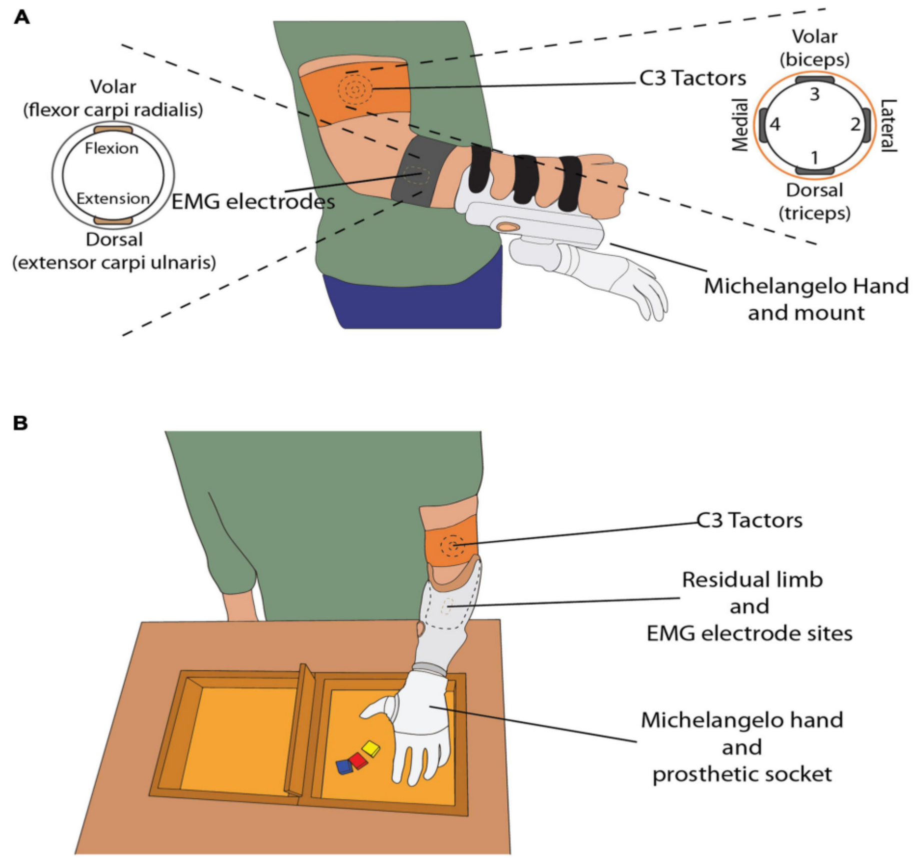


Main results: 87% accuracy already in the first session, with rapid learning.+30% precision in strength control with feedback compared to control without feedback. Stable performance even with muscles not specifically involved in hand function.

Conclusions: EMG-based vibrotactile feedback represents an effective, intuitive, and early applicable strategy, even in high-level amputations, for pre-prosthetic motor training and enhancement of myoelectric control.

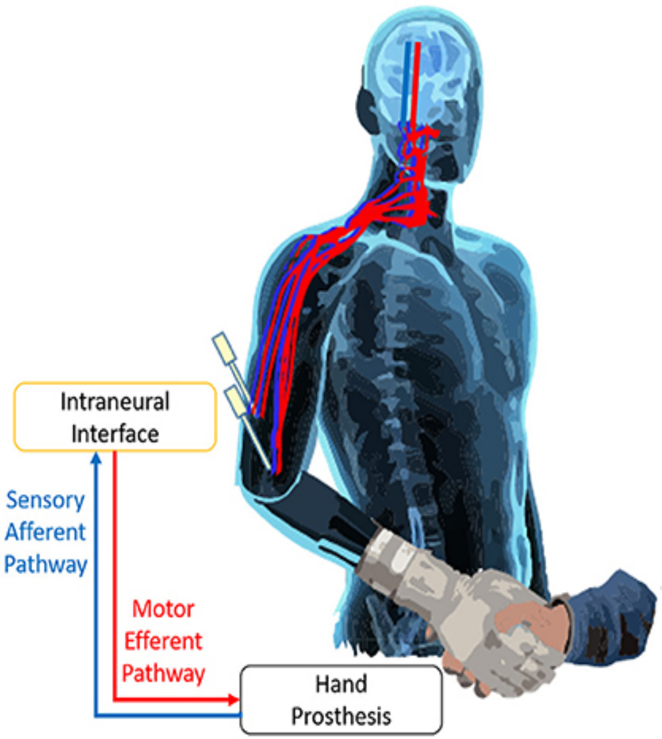
Tchimino et al., Scientific reports/Nature, 2024

Intraneural interfaces & bidirectional control

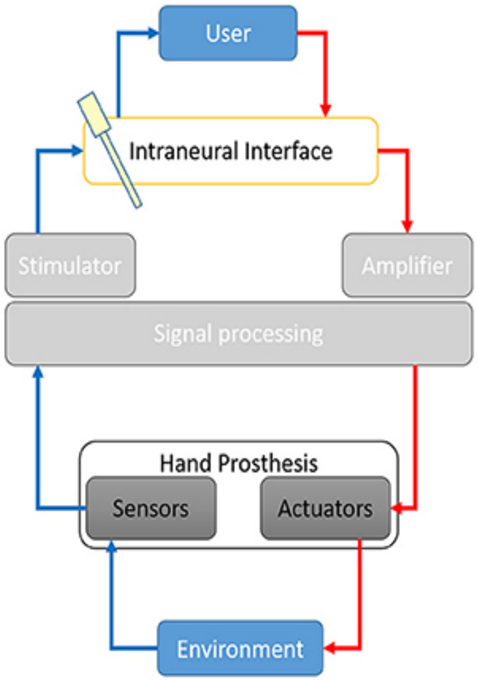
Intraneural interfaces allow selective and stable sensory restoration in amputees. Longitudinal studies report sustained perception of pressure, texture, and even limb position—fostering embodiment and reducing abandonment risk.

ü **TIME** (Transverse Intrafascicular Multichannel Electrodes) provide high-resolution tactile & proprioceptive feedback.
ü **Implanted interfaces** improve actualization, reduce phantom pain, and support long-term acceptance.
ü Clinical trials* demonstrate improved object recognition and fine grip control.

Raspopovic, et al. Science Translational Medicine, 2014.
Ortiz-Catalan, et al., The New England journal of Medicine, 2020).



Lotti, et al., Frontiers in Neuroscience, 2017



On the left: efferent motor signals (in red) travel from the central nervous system to the prosthesis via the intraneural interface, while afferent sensory signals (in blue) return to the nervous system to provide tactile feedback.

On the right: the user interacts with the prosthesis through the intraneural interface. *Motor commands* are amplified and processed to activate the prosthesis sensors and actuators. In turn, information from the environment and the sensors is conveyed back through intraneural stimulation, closing the sensorimotor loop.

"Intraneural sensory feedback restores grip force control and motor coordination while using a prosthetic hand"

Clemente, et al. J.Neural Eng. 2019

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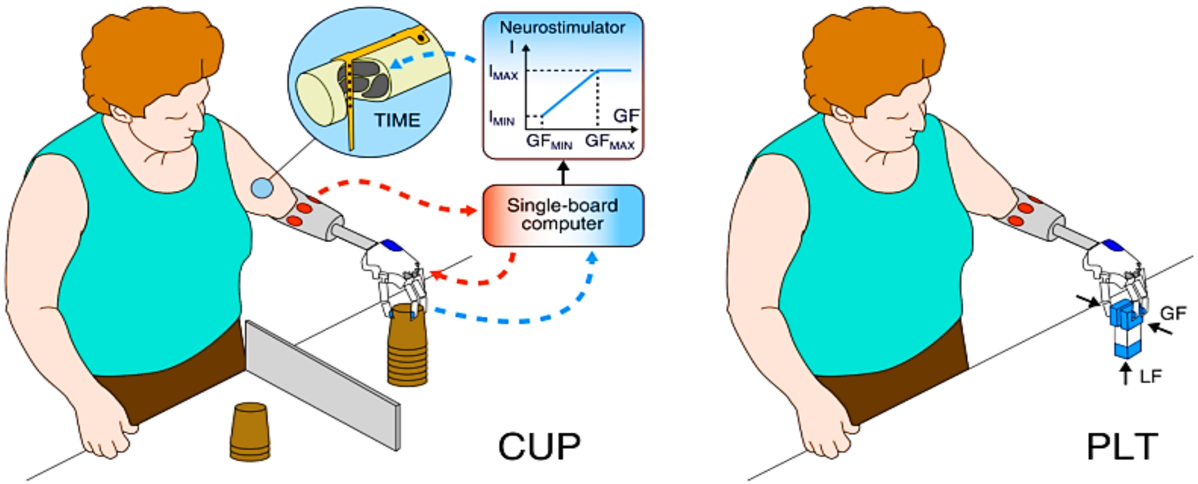
Study objective:
To test whether intraneural sensory feedback, delivered via ulnar nerve stimulation, improved grip force control and motor coordination in an arm amputee using a myoelectric prosthetic hand.



<u>Subject:</u> 53-year-old female, transradial amputation.

<u>Technology:</u> TIME electrode implanted in the ulnar nerve, stimulation proportional to grip strength.

Tests performed:

- Stacking Cups Test (CUP) – moving 10 cups, requires fine force control (≤2.2N).
- Pick and Lift Test (PLT) – lifting and lowering an object, measuring grip strength (GF) and loading force (LF), avoiding excessive force (>4.4N).

Conditions: with feedback (F-ON) vs. without (F-OFF), randomized.

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Tests performed:

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Ø Pick and Lift Test (PLT) – lifting and lowering an object, measuring grip strength (GF) and loading force (LF), avoiding excessive force (>4.4N).

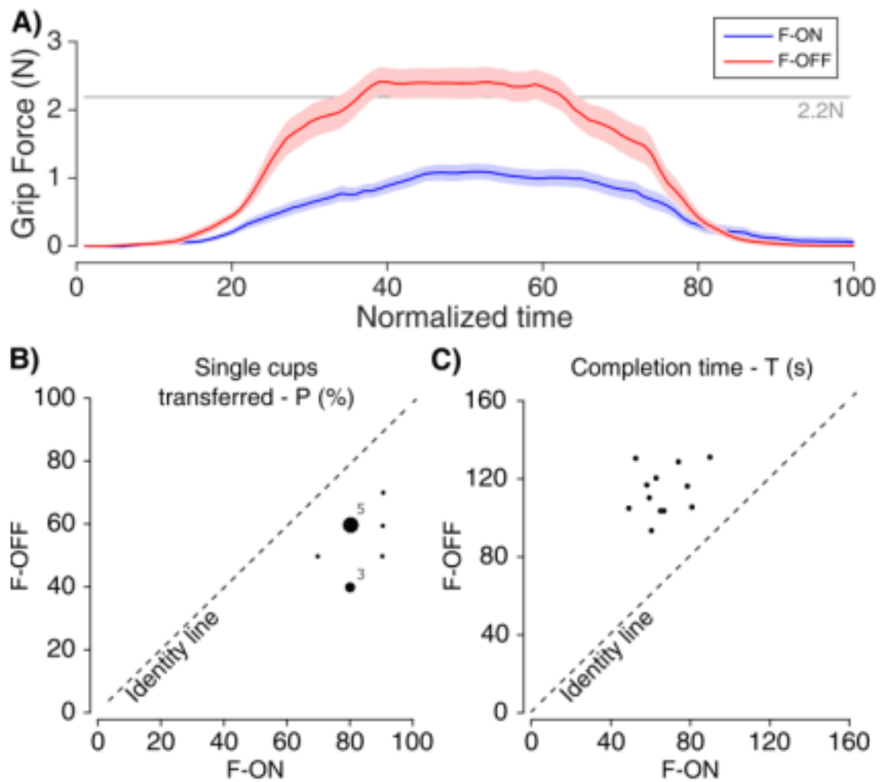
Conditions: with feedback (F-ON) vs. without (F-OFF), randomized.

CUP:

Ø More accurate grip: ~82% of single cups with F-ON vs. ~54% with F-OFF ($p < 0.001$)
Ø Faster times: ~67 s with F-ON vs. ~106 s with F-OFF ($p < 0.001$), improvement over time with feedback only.

PLT:

Ø Improved coordination: reduced delay between GF and LF (211 ms vs. 320 ms, –34%, $p < 0.001$)
Ø Faster loading phases: 330 ms with F-ON vs. 480 ms with F-OFF ($p < 0.001$).



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“Intraneural sensory feedback restores grip force control and motor coordination while using a prosthetic hand”

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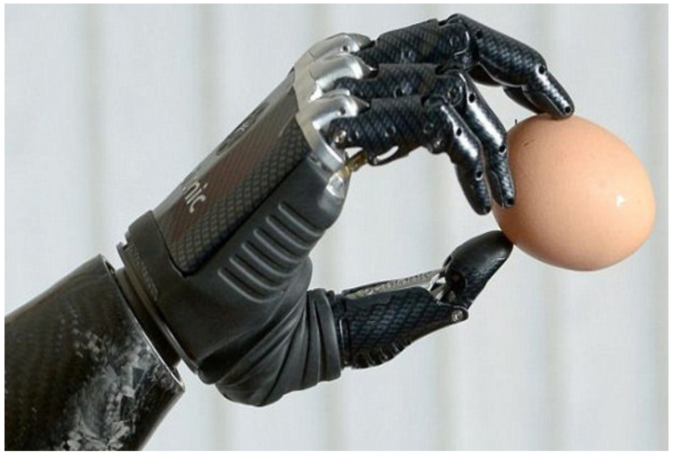
ü Intraneural feedback, although not perfectly somatotopic (vibration felt in the little finger, not the affected fingers), was integrated into motor control.

ü It allowed the patient to develop an internal representation of the task, with a predictive grasp similar to that of a natural human.

ü The ability to learn and transfer learned skills from one task to another was evident.

Implications:



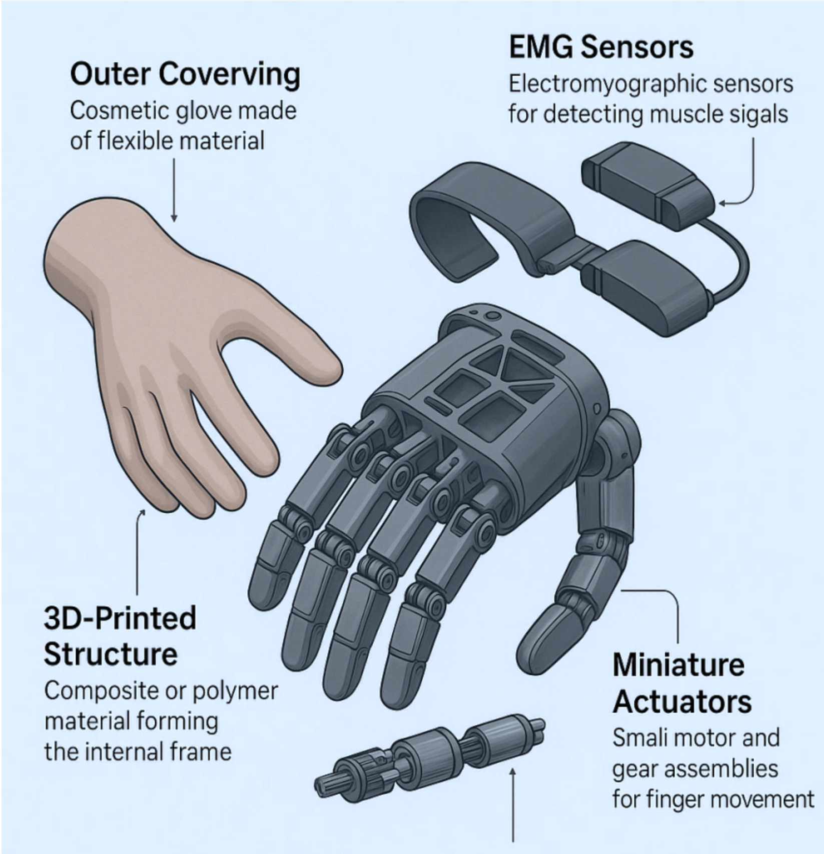
First systematic demonstration that a single intraneural creation channel can partially restore sensorimotor control in amputees.

Significant potential to improve the adoption of myoelectric prostheses by reducing cognitive fatigue.

Future studies: increased channels, more natural modalities, larger population, real-world prolonged use.

Manufacturing technologies for upper limb prostheses

- Modern prosthetics combine mechanical engineering, electronics, and advanced materials.
- Additive techniques such as 3D printing allow for customized, lightweight, and accessible designs.
- The use of composite materials, flexible polymers, and medical silicones improves comfort and adaptability.
- Motorized systems employ miniaturized actuators (tendons, brushless, pneumatic) to reproduce gripping movements.



Crawford, et al., Proceedings of the ASME 2010 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, 2011.

3D Printing, Why?

- **Customization**: tailored to patient's anatomy and functional needs
- **Lightweight materials**: improved comfort and wearability
- **Cost-effectiveness:** affordable production compared to traditional manufacturing
- **Rapid prototyping**: faster design–test–redesign cycles
- **Accessibility**: increased availability, especially in low-resource settings
- **Integration**: possibility to embed sensors, actuators, and soft materials for advanced control

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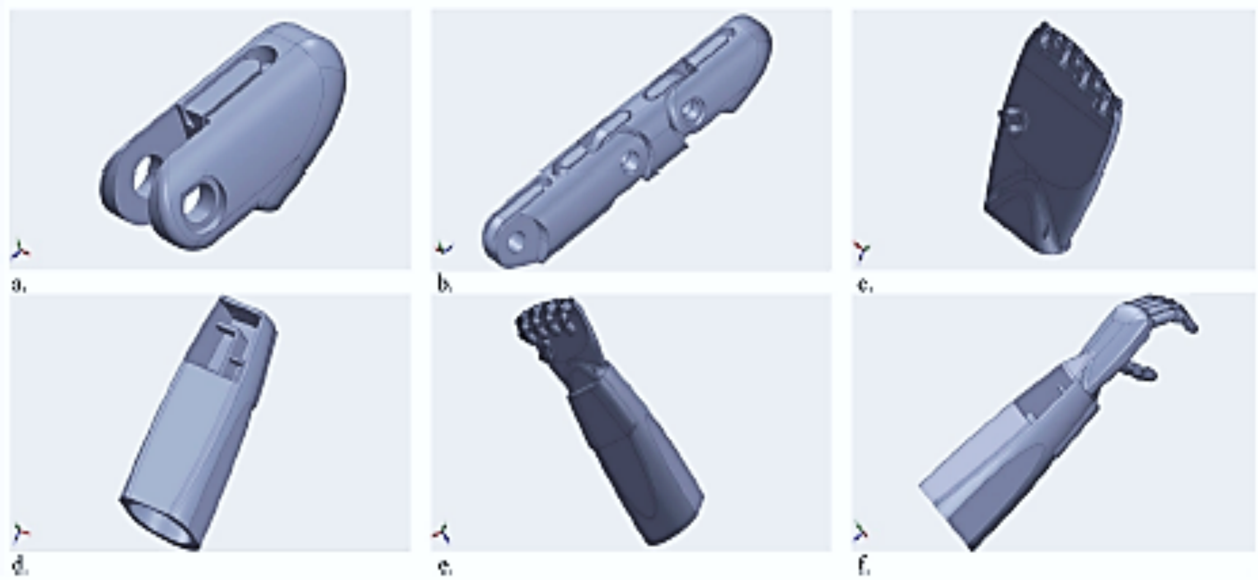
"The effects of vibrotactile feedback on task performance in a 3D-printed myoelectric prosthetic arm"

Sidney Nguyen, Henrik Malmberg. Journal of Emerging Investigators. 2019

Manifacturing:

- Ø A myoelectric artificial hand designed for a person with a left forearm amputation.
- Ø It was made entirely through 3D printing with ABS plastic, a durable and lightweight material.
- Ø The structure comprises five fingers that move simultaneously thanks to a single electric motor, allowing for a simple yet effective hand closure, although the fingers lack independent movement.



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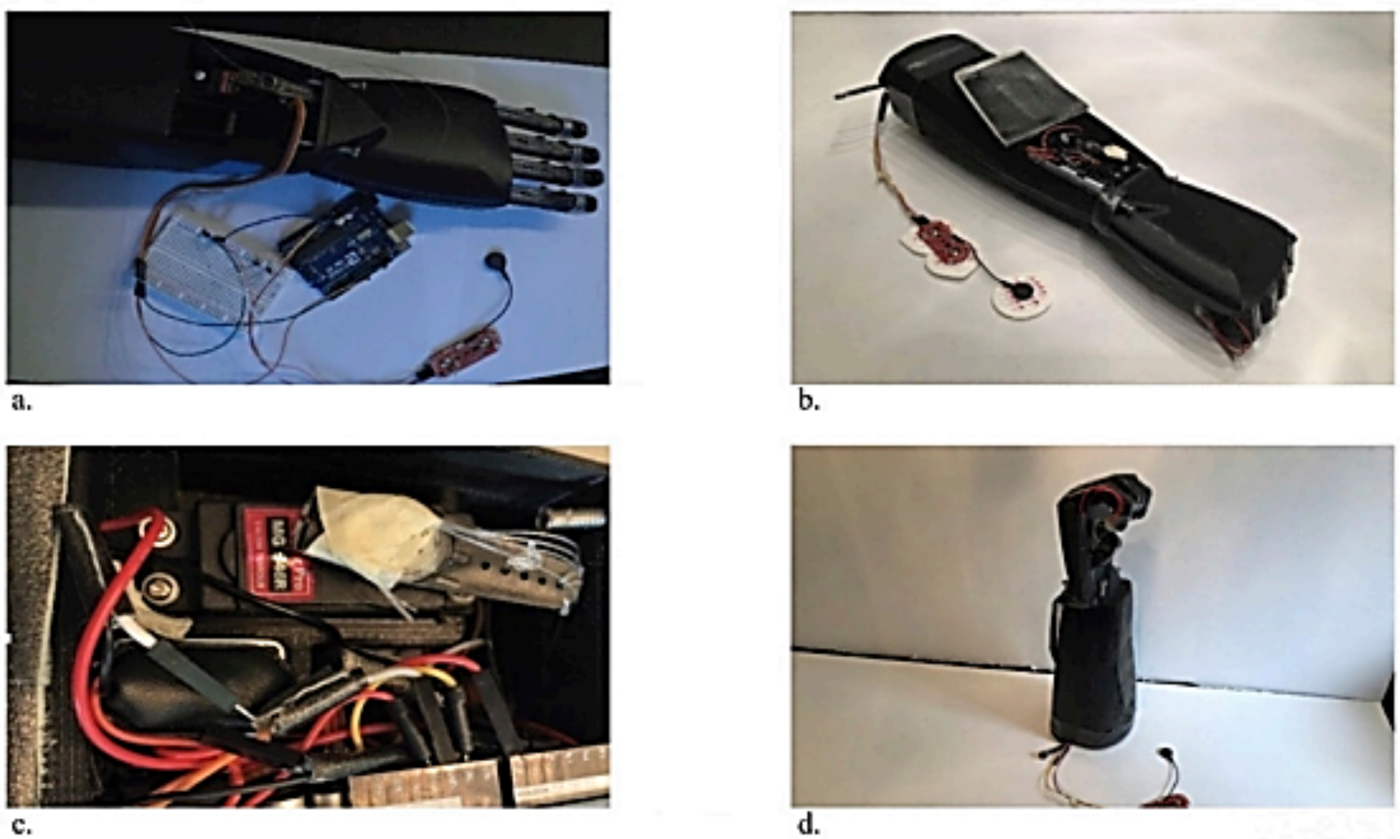
Control:

The prosthesis is controlled via myoelectric signals (EMG), detected by a sensor placed on a residual muscle of the user. These signals are sent to an Arduino* board, which regulates the motor's movement.

The speed of the hand's closure depends on the intensity of the muscle contraction: the stronger the contraction, the faster the hand closes.



*Arduino is a low-cost, open-source microcontroller for prototyping and control.

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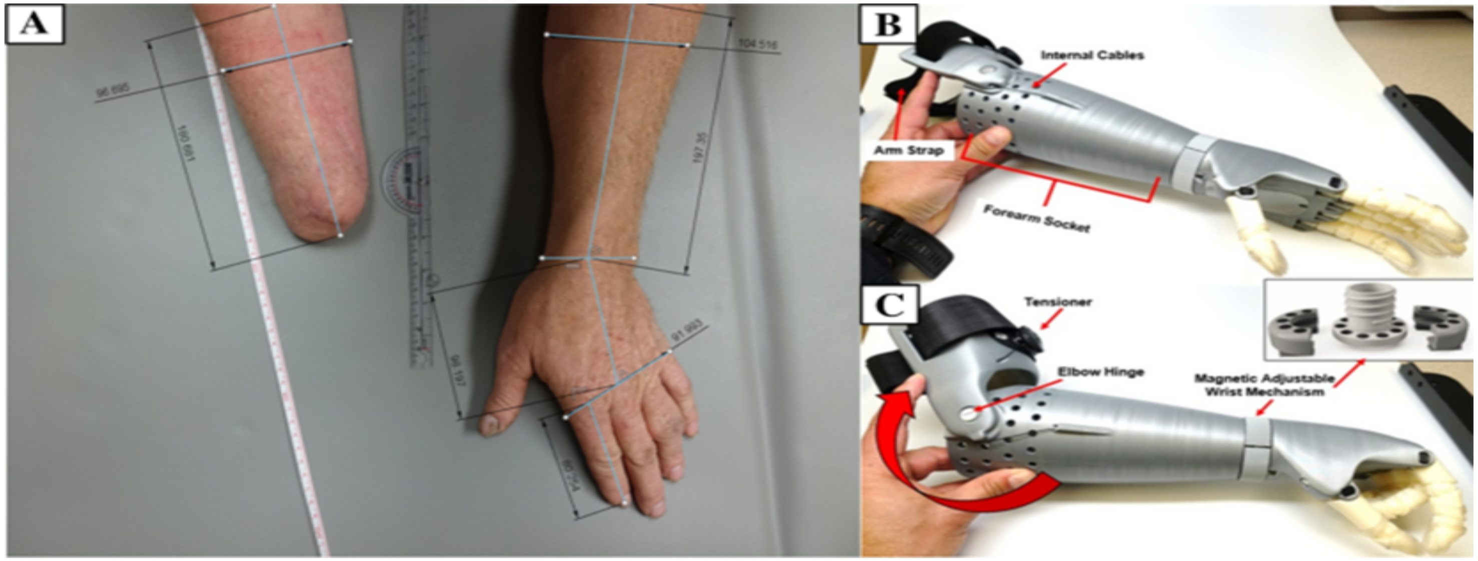
“Functional performance and patient satisfaction comparison between a 3D printed and a standard transradial prosthesis: <u>a case report</u>”

Copeland et al., BioMedical Engineering OnLine, 2022

<u>Study Objective</u>: to compare the functional performance and patient satisfaction between a traditional transradial prosthesis and a 3D-printed prosthesis, designed and fitted remotely.

Man, 59 years old, traumatic transradial amputation of the dominant limb.
Traditional prosthesis: used 4–5 hours/day for 5 weeks. *3D prosthesis*: used 6 hours/week for 5 weeks.



Traditional prosthesis: mechanical hook, clinic fitting, control with shoulder and scapula.
3D prosthesis: functional hand terminal, PLA printing, remote fitting via photogrammetry.

“Functional performance and patient satisfaction comparison between a 3D printed and a standard transradial prosthesis: a case report”

Copeland et al., BioMedical Engineering OnLine, 2022

Control: voluntary closure through flexion of the residual elbow.

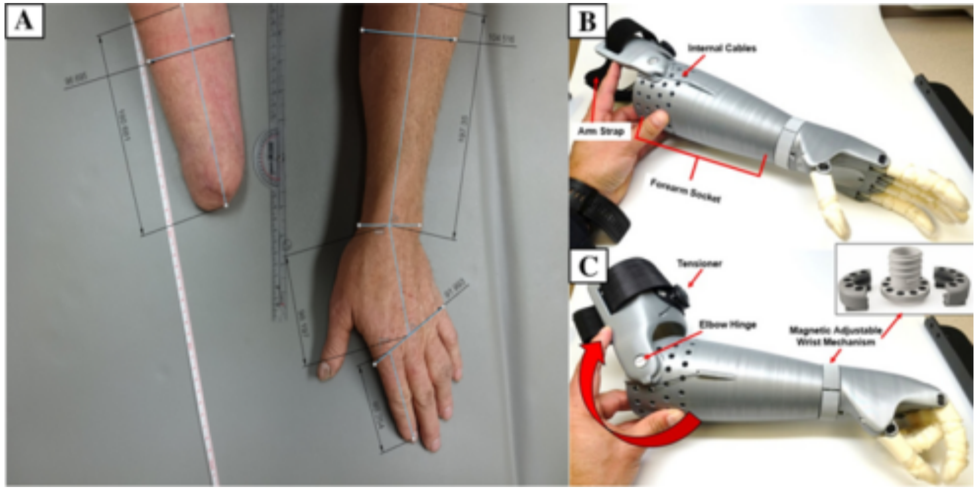
Functional tests: Box and Block Test.
Bimanual Coordination Tray Test (bimanual coordination).

Satisfaction: QUESTIONNAIRESQUEST 2.0
satisfaction with the device and services.

OPUS: comfort, aesthetics, functionality, maintenance.

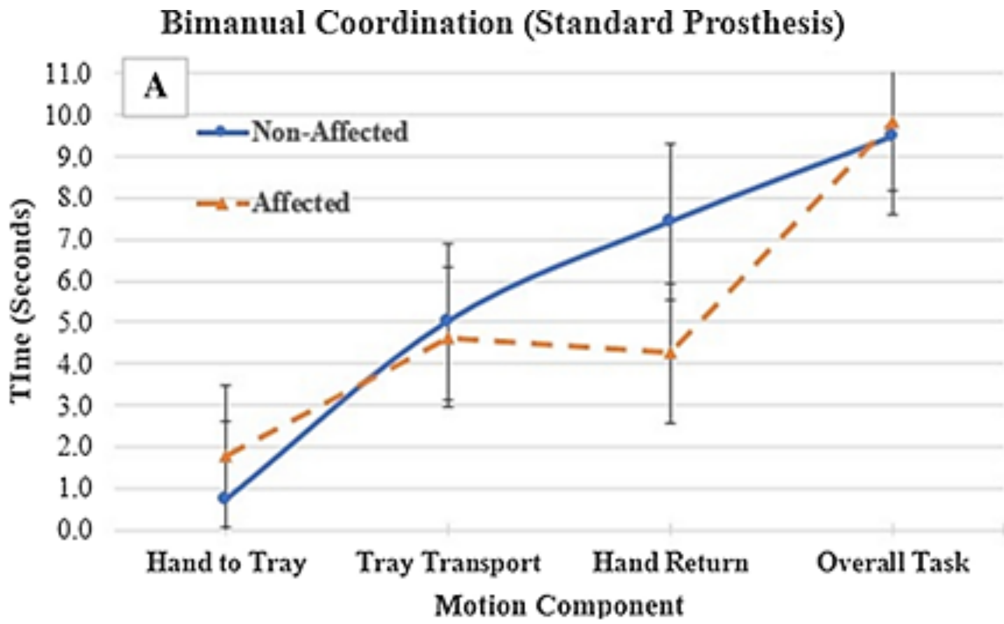
A-C: Participant using a hand prosthesis (standard VS 3D-printed) to grasp the blocks.

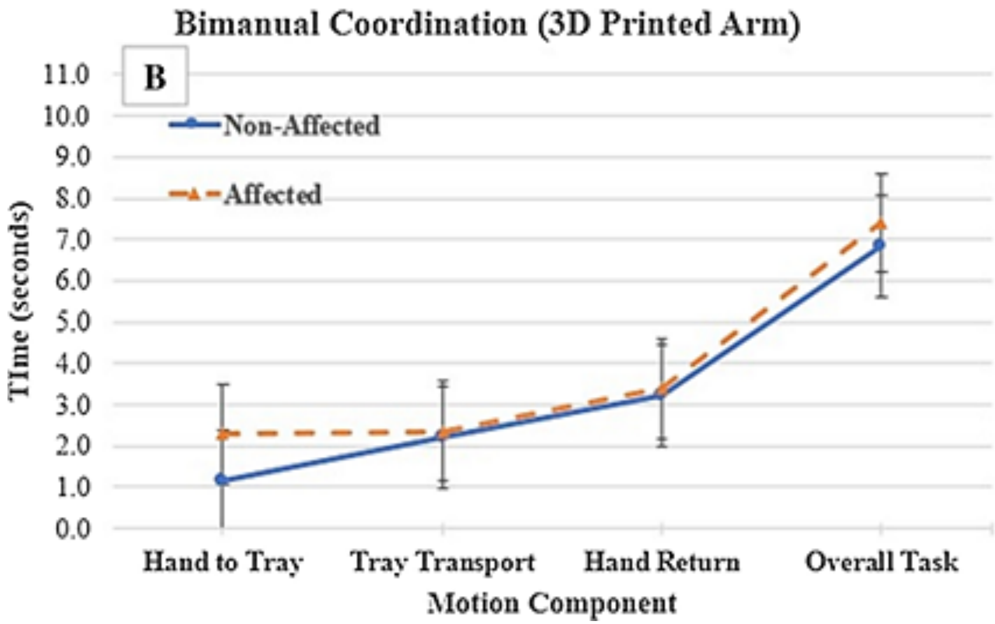
B-D: Side view during functional task performance with hand prothesis (standard VS 3D-printed).



- **Functional Performance**:
3D Prosthetics > Traditional in the Box and Block Test → 17 blocks/min vs 12.3 blocks/min.

- **Bimanual Coordination**: similar but there is an advantage of 3D





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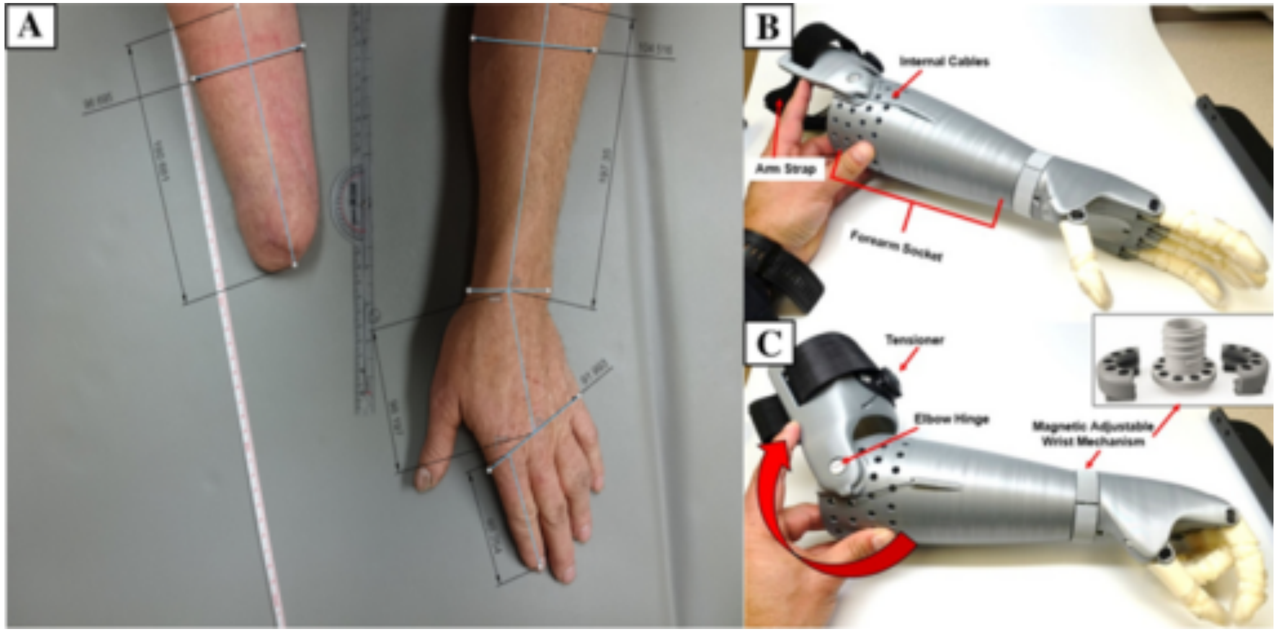

ü **Patient Satisfaction**:

ü Traditional > 3D in terms of:

- Durability;
- Perceived efficacy
- Dexterity for complex activities

ü 3D > Traditional for:

- Aesthetics Lightness Ease of wear.

§ 3D prosthetics are effective in gross tasks but less so in activities requiring fine movements and high grip strength.

§ 3D printed prosthetics, although less esteemed in terms of overall satisfaction, improve functional performance in daily tasks and offer:

- Fast production times (2 days),
-remote fitting,
-reduced costs.

They represent a promising solution as postoperative transitory prostheses, especially in rural contexts or with limited resources.

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“The effects of vibrotactile feedback on task performance in a 3D-printed myoelectric prosthetic arm”

Sidney Nguyen, Henrik Malmberg. Journal of Emerging Investigators. 2019

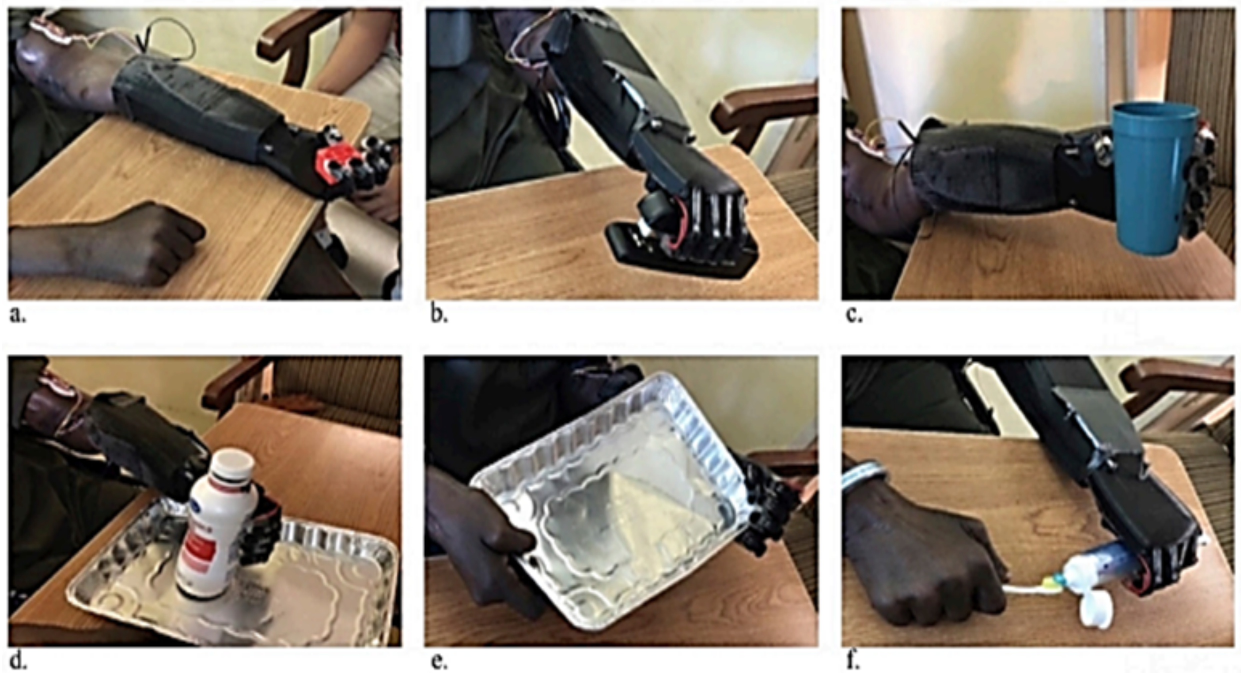
One of the device's most interesting innovations is the addition of a **vibrotactile feedback system**:

→ when the prosthetic index finger touches an object, a small vibrating motor mounted on the user's arm activates, transmitting a perceptible vibration.

This signal helps the user understand the moment of contact with an object, thus compensating for the lack of natural sensitivity typical of conventional prostheses.

The user performed functional tasks in two conditions: blindfolded and unblinded, and both with and without vibrotactile feedback.

The results showed that, in the absence of vision, the user was unable to complete any task without feedback. However, with the vibration activated, she was able to successfully complete all tasks.
In conditions of normal vision, the presence or absence of feedback did not significantly affect performance.



the vibrotactile system is particularly useful when the user cannot rely on vision

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Sidney Nguyen, Henrik Malmberg. Journal of Emerging Investigators. 2019

From an economic standpoint, the prosthesis is extremely accessible, with a total cost of less than $160. This makes it an attractive solution for those with limited resources.

ü ease of use
ü quick learning
ü low cost
ü customization options
ü guaranteed basic functionality

x absence of complex finger movements
x lack of wrist rotation
x the binary nature of the feedback (vibrate/yes or no), which provides no information about the strength or quality of contact.

This prosthesis represents a concrete example of a functional, low-cost device that can be adapted to individual needs, offering greater autonomy to people with amputations.

The use of vibrotactile feedback has demonstrated a real positive impact on the user's performance in complex conditions.

Clinical summary of technological benefits

These technological advances are not just engineering feats — they directly support functional independence, reduce cognitive effort, and restore critical sensorimotor functions essential in prosthetic rehabilitation.

Soft robotics:
better usability and wearability

Tactile feedback:
improved grip control and task precision

Proprioceptive feedback:
enhanced motor planning and stability

Neural interfaces :
restored sensation and reduced phantom pain

IRCCS San Raffaele

Thank you for your attention

Research Area in Neuromotor and Robotics

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Clinical assessment of hand function

These tests are all **validated** and used in **clinical settings** with **various populations**. They are also employed in **numerous research studies**

Box and Block Test (BBT)

Manual dexterity test used to assess eye-hand **coordination**, **speed**, and **gross motor skills** of the upper limbs. The participant must transfer as many blocks as possible from one compartment to another within 60 seconds, using one hand at a time.

(Mathiowetz, et al. 1985a)

Nine Hold Peg Test (BBT)

A **fine motor dexterity** test that measures the **ability** to handle small objects. The participant must insert and remove nine pegs into nine holes as quickly as possible, first with one hand, then with the other.

(Mathiowetz, et al. 1985b)

Purdue Pegboard Test (PPT)

Measures **bimanual dexterity**, **fine motor coordination**, and **speed** of execution. The test involves placing pegs, washers, and collars into holes on a board, using one or both hands depending on the task.

(Tiffin & Asher, 1948)

Instrumental assessment of hand function

Kinematic analysis with stereophotogrammetric system
Technique used to objectively study the (3D) movement of the human body

Electromyography (EMG)
Diagnostic test that studies the electrical activity of muscles

Instrumental assessment validated for clinical use (CE marking)

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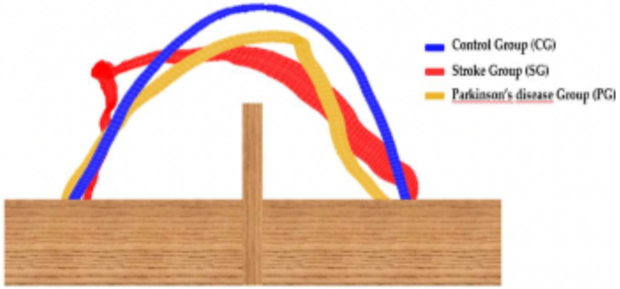
Instrumental assessment of hand function: Inertial Measurement Units (IMU)

Wearable sensors that measure and record the movement and orientation of a body in space

Study of upper limb kinematics during the Box and Blocks Test in individuals with stroke, Parkinson's disease, and healthy subjects
(Cocco et al., 2024)



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Comparative analysis of upper body kinematics in stroke, Parkinson's disease, and healthy subjects: An observational study using IMU-based targeted box and block test

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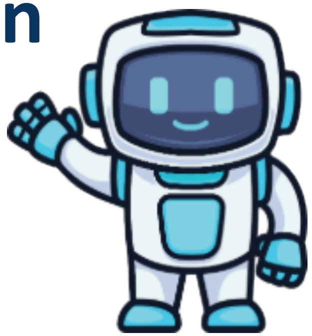
Benefits of Instrumental assessment in Clinical Practice



- **Data Objectivity :** The results do not depend on the clinician’s subjective observation, but on precise and repeatable measurements

- **High Precision :** Sensors, motion capture systems, EMG, and other devices detect biomechanical or physiological parameters with high accuracy

- **Longitudinal Monitorin:** Allows reliable comparison of data across multiple sessions (pre/post treatment, follow-up, etc.)

- **Support for Clinical Decision-Making:** Quantitative data help doctors and therapists define or adjust more effective treatment plans

- **Personalized Treatment:** The rehabilitation plan can be tailored to the specific needs of the patient based on real data

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Instrumental assessment of hand function

Developed Instrumented Gloves

Enable precise and realistic tracking of hand and finger movements, providing immersive virtual experiences

- Easy and fast integration
  Ability to record, edit, and export sessions in various formats
- Professional synchronization during recording
- Start and synchronize **finger tracking** directly from Shogun, ensuring perfectly aligned tracking between hands and body

Instrumental assessment not yet validated for clinical use

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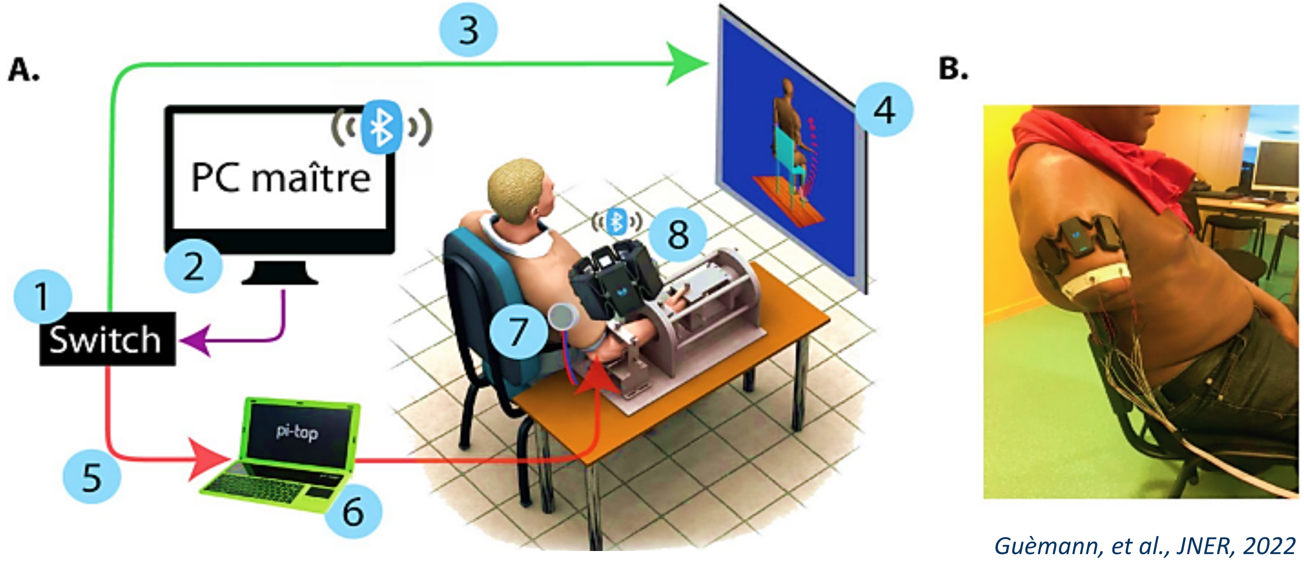
Proprioceptive feedback integration

By integrating proprioceptive cues, prostheses help restore the internal model of limb position. This leads to improved motor coordination, especially when visual attention is divided — as often occurs in real-life environments.



Guèmann, et al., JNER, 2022

A. Experimental setup

1. Switch – network connection unitMaster
2. PC – main computer controlling the system
3. Bluetooth link – wireless communication between PC and rehabilitation device
4. Display – visual feedback provided to the patient
5. Connection to pi-top – secondary computer interface
6. pi-top device – auxiliary processing unit
7. Robotic interface – rehabilitation device applied to the patient's arm
8. Sensors/actuators – modules integrated into the robotic system for control and monitoring

B. Patient application.

Example of the wearable interface with sensors/actuators attached to the patient's arm during the rehabilitation protocol.

Upper limb robotic rehabilitation

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Robotic glove for hand rehabilitation

- Sensory robotic glove that allows for movement in different modalities.
- Mirror therapy and action observation.
- Thus, promoting neuroplasticity and functional recovery.

Studies by Vanoglio et al. (2017) and Lee et al. (2021) highlight the benefits of the sensory glove (SG): improved dexterity, muscle strength, reduced spasticity, as well as a significant improvement in proximal upper limb motor function and post-stroke performance.

3D Printing Techniques for Hand Prostheses

- FDM (Fused Deposition Modeling)
  - *Most common, low-cost, versatile.*
  - *Suitable for lightweight plastic components*
- SLA (Stereolithography)
  - *High resolution and smooth surfaces*
  - *Ideal for detailed prototypes and molds*
- SLS (Selective Laser Sintering)
  - *Strong and durable parts.Allows complex geometries without support structures*
- PolyJet / Multi-material
  - *Combines rigid and flexible materials. Useful for realistic prototypes integrating soft parts*
- Metal 3D printing (SLM, EBM)
  - *For robust, long-lasting components (e.g., joints, connectors)*