A soft supernumerary hand for rehabilitation in sub-acute stroke: a pilot study on spasticity

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Research Article

Keywords:

Posted Date: February 24th, 2022

DOI: <https://doi.org/10.21203/rs.3.rs-1369771/v1>

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Abstract

In sub-acute stroke patients, task-specific training is the most effective rehabilitation treatment for the upper limb. However, in those patients with severe paresis and initial spasticity, task-specific training could increase the risk to develop severe spasticity in the following months.

Four sub-acute patients, at high risk of developing spasticity, underwent task-specific training using a supernumerary, aesthetically and functionally anthropomorphic, soft robotic hand (SoftHand-X), driven by the residual movements of the patient's paretic hand. A 1-year follow up was done.

All subjects presented a remarkable recovery of upper limb function. No worsening of spasticity was found. The proposed SoftHand-X-based rehabilitation technique for task-specific training in sub-acute stroke patients does not increase the risk of developing severe spasticity.

Introduction

Stroke is the leading cause of disability in western society [1]. Six months after stroke, approximately 50% of patients remain with a chronic reduction of arm function [2]. That reduces their independence and quality of life significantly [3]. Therefore, improving upper limb function is a core element of stroke rehabilitation.

The natural course of clinical recovery after stroke reflects the ability of the neuronal network to adapt plastically to injury [4]. Observational studies show that recovery is more rapid during the first month after stroke, and motor function typically reaches a plateau within three months [5]. Compelling evidence state that the first three months after stroke (acute and sub-acute phases) may represent a critical window for rehabilitation to maximize recovery of body functions and activities [6, 7].

It is widely accepted that upper limb motor training should draw inspiration from the principles of motor learning to promote neural plasticity and functional improvement. According to these principles, repetitive and intensive functional tasks should be used, including grasping exercises (task-specific training) [8]. Task-specific training has been proven to speed up the process of motor recovery in post-stroke patients [9]. Therefore, delivering task-specific training within the first three months after stroke is crucial to promote upper limb functional recovery.

Unfortunately, muscle hypertonia begins to appear in the same first three months after the stroke when rehabilitation could obtain its best since the plastic mechanisms underlying the recovery of function are most active. Secondary soft tissue changes in muscles, tendons, and ligaments can cause what is usually referred to as intrinsic hypertonia [10]. However, compelling evidence shows that increased stretch reflex activity partially causes velocity-dependent hypertonia [11] (i.e. an increase in muscle tone that becomes more apparent with more rapid stretching movements) in the overwhelming majority of stroke patients. Velocity-dependent hypertonia includes both spasticity and spastic dystonia. Spasticity is due to stretch reflex exaggeration. Moreover, Patients affected by spastic dystonia cannot relax their muscles,

which spontaneously contract at rest [12]. On the contrary, in healthy subjects, the stretch reflex cannot be evoked during muscle tone assessment [13].

At its onset, which usually happens in the first few weeks after stroke, hypertonia is generally mild and does not cause disability. While the prevalence of muscle hypertonia peaks at four weeks after stroke, the number of patients with severe muscle hypertonia continues to increase during the first year [14]. At one year after stroke, severe spastic dystonia of fingers, wrist, and elbow flexors can hinder function, and result in pain and complications, requiring chronic treatment with botulinum toxin.

The association between muscle hypertonia and severe motor impairment in the first three months after stroke is an important predictor of the possible development of severe hypertonia one year after stroke [15]. Patients who in the first three months after stroke present such clinical association represent a real challenge for neurorehabilitation. In order to facilitate sensory-motor recovery, it is essential to treat them with task-specific training, including grasping exercises. Obviously, due to the severe motor deficit, such patients can perform task-specific training only in an assisted manner, that is, with the help of the physiotherapist. That is especially true for hand movements since the motor deficit is usually more pronounced in the distal muscles. On the other hand, there is the concern, deeply felt by physiotherapists, that in such patients the execution of repeated and intense grasping exercises may aggravate hypertonia in flexor muscles of the wrist and fingers [16]. Indeed, in subacute stroke patients with severe-moderate upper limb impairment, it has been reported a muscle tone increase after rehabilitation treatment [17].

Robotics is a promising approach to poststroke rehabilitation. It may be used to deliver or enhance task-specific training [18]. Robots for upper limb training can be differentiated into exoskeletons and end-effector robots. While exoskeletons control one or more joints of the paretic limb by means of torque actuators, end-effector robots guide only the most distal part of the paretic limb. A recent meta-analysis states that, in comparison with non-robotic treatment, robotic rehabilitation of the upper limb produces a positive effect on motor control and muscle strength of the paretic limb, but a negative effect on hypertonia [19].

Besides exoskeletons and end-effector robots, supernumerary Robotic Limbs (SRLs) represent a new frontier in robotics. They constitute a new type of wearable robot, which augment the human body by providing additional robotic limbs or fingers. Unlike exoskeletons, supernumerary robotic limbs do not request any joint-to-joint alignment. Moreover, they do not force the user to follow a specific trajectory with their own body parts. SRLs have been initially proposed for industrial purposes to improve users' ergonomics and enhance their capabilities [20, 21]. More recently, SRLs have been used in chronic stroke patients for compensating their missing abilities and counter learned non-use [22, 23]. To date, SRLs have never been used in post-acute stroke patients to promote neural plasticity and functional improvement.

This pilot study represents the first attempt to use a supernumerary robotic hand in patients with subacute stroke (see Fig. 1). Patients with severe hand weakness and initial hypertonia were enrolled, therefore being at high risk of developing severe hypertonia of wrist and fingers flexors in the following months. In our protocol, full finger extension of the robotic hand was activated by the patients through

their residual, albeit minimal, active extension of fingers or wrist, while the patients were required to relax their muscles to achieve full flexion of the robotic fingers. Our idea is that, following this protocol, patients could be able to perform task-specific training including grasping exercises, which is known to promote motor recovery, without any overt activation of flexor muscles of fingers and wrist, whose intensive and repetitive activation could favor the development of severe hypertonia in the following months. Moreover, the visual input provided by the robotic hand could activate the mirror neuron system of the affected hemisphere, which is thought to play an important role in motor learning and rehabilitation [24]. This can be compared to the classic Mirror Therapy, widely used in post-stroke rehabilitation, which is based on the movements of the unaffected hand reflected on a mirror placed in the patient's midsagittal plane to provide the illusion of movement of the affected hand [25]. The advantage of our new approach could consist in the fact that the movement, albeit assisted, is induced by the voluntary activation of the affected hemisphere. Our idea can also be compared with the use of immersive or non-immersive virtual reality (VR) for stroke rehabilitation, which has been demonstrated effective in combination with conventional therapy [26, 27]. In our case, the positive effects of the reinforcement of the visual input in causal association with the motor commands, at the basis of VR therapy, could be further strengthened by the matching residual kinaesthetic feedback from the patient's arm. Furthermore, the actual possibility to perform functional tasks in the real world could provide positive motivational reinforcement.

The first aim of this pilot study is to assess the short-term and long-term effects of this novel rehabilitative approach on the muscle tone of wrist and fingers flexor muscles. Accordingly, the primary outcome is the clinical assessment of muscle tone using the Modified Ashworth Scale (MAS). The secondary outcome is the EMG assessment of spasticity and spastic dystonia. The second aim is to evaluate the feasibility of the treatment by investigating patients' compliance.

Our hypothesis is that the proposed treatment does not worsen hypertonia. If this hypothesis were confirmed, then we could plan a randomized controlled trial in patients with subacute stroke to evaluate the effectiveness of the treatment with the robotic hand on functional recovery.

Results

In compliance with the inclusion criteria, the 4 subjects enrolled were unable to grasp and release objects. Instead, using SoftHand-X, they became able to perform these tasks and could follow an intensive rehabilitation program focused on grasping and releasing objects of various shapes and sizes. None of the participants experienced any adverse effect during the 10 treatment sessions (5 days a week for 2 weeks). The feasibility of using SoftHand-X was assessed measuring the level of patients' participation to the treatment, by means of the Pittsburgh scale [28]. The median scores recorded among the 4 patients was 6, meaning "excellent participation in all exercises with maximal efforts, finishing all exercises, and taking an active interest in exercises and/or future therapy sessions".

The possibility of treating these patients with an intensive protocol focused on grasping and releasing objects raises the issue of spasticity in flexor muscles of the wrist and fingers. In fact, these subjects at

baseline were at high risk of developing a disabling form of spasticity in the following months [15] and there is concern that intensive exercise of the distal flexor muscles involved in grasping tasks could facilitate this progression [16]. For this reason, we made sure that SoftHand-X was controlled only by the activation of extensor muscles.

Figure 2 shows the clinical scores of the 4 patients evaluated at the 4 times points: just before the beginning of the treatment (T0), just after the last session (T1), 10 days after the last session (T2) and 1 year after stroke (T3). A mean improvement in the motor score of the Fugl-Meyer Assessment for upper extremity (FMA-UE) (17) of 11 points from T0 to T1, 7 points from T1 to T2 and 23.3 points from T2 to T3 was observed, with an improvement of the hand/wrist motor sub-score of 5.8 points from T0 to T1, 2.3 points from T1 to T2 and 13.3 points from T2 and T3. Moreover, patients were also characterized by an increase of Medical Research Council (MRC) scores indicating a progressive improvement (from T0 to T3) of strength in flexor-extensor muscles of the wrist and fingers. At T0, two patients (1 and 4) showed an MAS score of 1 (mild spasticity) in flexor muscles of both wrist and fingers, while the other 2 patients showed an MAS of 1 only in wrist flexors. A decrease of the MAS score from 1 to 0 (no spasticity) was observed at T1 and at T2 in all 4 patients. At T3, only in patient 3 a mild spasticity in wrist flexors (MAS 1) reappeared.

EMG assessment of muscle tone (see Fig. 3) showed, at T0, a stretch reflex not preceded by a tonic muscle contraction in all 4 patients, thus indicating spasticity [12, 13]. In the first two patients, spasticity disappeared immediately after treatment (T1) and never returned (T2 and T3). In patient number 3, spasticity decreased after treatment (T1 and T2), while at the last evaluation (T3) it was slightly more intense than at baseline. Finally, in the last patient, spasticity disappeared immediately after treatment (T1), it reappeared 10 days after the end of treatment (T2), while it was not present at the last assessment (T3).

Discussion

These results state that our 4 patients presented a remarkable recovery of the motor function of the upper limb. At the end of the study, one year after stroke onset (T3), all had achieved excellent motor control of the upper limb, practically without any residual disability or with slight residual disability. Obviously, the data of this pilot study, carried out on 4 subjects and without a control group, do not allow us to say whether and to what extent the rehabilitation treatment contributed to the achievement of this positive outcome. However, the temporal course of spasticity (evaluated both clinically and neurophysiologically) shows that the rehabilitation treatment with SoftHand-X does not induce any worsening of spasticity, either in the short- or long-term, suggesting instead that such treatment may even improve spasticity.

The main limitation of this study is the small sample size. However, our intention was to enroll a very homogenous group of patients, at high risk of developing severe hypertonia.

Since no worsening of spasticity was observed, thus confirming our hypothesis, a randomized controlled trial in patients with sub-acute stroke can now be planned to evaluate the effectiveness of SoftHand-X on

functional recovery.

Methods

Participants

According to the aim of this pilot study, inclusion criteria were:

- first-ever stroke, occurred no longer than 2 months before the enrolment
- ischemic or haemorrhagic lesions confirmed by computed tomography or magnetic resonance imaging
- severe weakness of the flexor-extensor muscles of the fingers, with inability to grasp objects
- ability to perform minimal active extension movements of the fingers or wrist, covering at least 5 degrees of the corresponding passive range of motion
- increased tone in flexor muscles of the fingers or wrist, defined as an MAS score higher than 0
- no severe cognitive impairment (Mini Mental State Examination-MMSE- > 24 points) and no severe aphasia

All 4 participants (Table 1) gave written informed consent to the study that was conformed to the Declaration of Helsinki and was approved by the ethical committee of “IRCCS-Ospedale Policlinico San Martino, Genova, Italia” (approval number 258REG2017).

Table 1
Demographic and clinical characteristics of patients.

	Age (years)	Sex	Stroke type	Paretic side	Time between stroke onset and T0 (days)
Patient 1	57	Female	Haemorrhagic	left	50
Patient 2	68	Male	Ischaemic	left	45
Patient 3	74	Male	Ischaemic	left	18
Patient 4	58	Male	Ischaemic	left	60

Robotic hand

The SoftHand-X (SoftHand eXtrathesis) is a derivation of the robotic hand prosthesis SoftHand Pro [29]. The hand has 19 independent joints that approximate well the position and range of the main articulations of the human hand. The hand design and control are based on the concept of soft synergies [30], which in turn draws from the analysis of human motor control organization in synergies [31] and from the equilibrium point hypothesis [32]. The implementation of this concept through a morphological intelligence approach to the hardware and firmware design makes the overall control of the hand

extremely simple: a single open/close input from the patient can control all the 19 independent joints. The hand is capable of morphing itself around objects of different shapes and sizes, grasping and manipulating them in different functional ways. Soft robotics techniques and materials employed in the construction of the hand also make the fingers resilient to impacts and joint dislocations and contribute to the feeling of compliance and naturalness in physical social and self-interaction [33]. These characteristics, together with a carefully manufactured cosmetic glove, make for a high degree of anthropomorphism of the hand both aesthetical and functional.

The SoftHand X is a lightweight derivation of the prosthetic hand for desktop use, fitted with a splint to the patient's forearm. Overall dimensions of the SoftHand X are: 20 cm (palm + middle finger length), 10 cm (palm width) and 5 cm (palm thickness). Maximum grasping forces are: 80 N power grasp (cylindrical object, diameter 80 mm), 30 N pinch grasp (flat object, height 2 mm). Weight: around 500 g. The SoftHand X is powered by a Maxon Motor DCX22S equipped with a GPX22 planetary gearbox. An Austrian Microsystem magnetic encoder is used to read the position of the motor and close the control loop. A custom electronic board drives the hand and interfaces with input devices. Many different types of input devices can be used to detect the patient's grasp intention and drive the hand, ranging from EMGs in different locations to force handles, bending sensors, and triggers [23].

Input interface

In order to control the opening and closing of Soft-Hand X, in this pilot we used an input method based on the measurement of the extension of the fingers or the wrist of the affected side. A bending sensor (resistive flex Sensor, Spectra Symbol) was placed at the proximal interphalangeal joints (middle or index finger) or at the metacarpophalangeal joints (middle finger), depending on where it was easiest to detect an extension movement of at least 5 degrees. If this was not possible, then the sensor was placed on the wrist joint. The detection of the extension movement by the sensor determined the complete opening of the fingers, while the return to the starting position (induced by the relaxation of the extensors) determined the closing of the fingers.

Treatment with the robotic hand and conventional treatment

During the treatment with the robotic hand, the patient was sitting on a chair in front of a table. The treatment was based on a few specific tasks (ranging from 2 to 4, according to subject's compliance and capacity), which were intensively practiced for several repetitions. The tasks involved reach to grasp and object manipulation, including such tasks as putting pegs into holes, stacking cones and checkers. The proximal part of the upper limb, for example the arm and, if necessary, also the forearm, was supported by the physiotherapist, who helped the patient in the postural part of the task. The part of the task involving grasping and manipulating objects was instead performed entirely by the patient through the robotic hand (Fig. 1). The treatment session lasted one hour. Every patient received 10 treatment sessions, 5 a week, for 2 weeks.

In parallel to the treatment sessions with the robotic hand, patients followed the usual daily rehabilitation treatment for subacute stroke inpatients at the “Clinica di Neuroriabilitazione, Ospedale Policlinico San Martino, Genova”. This usual rehabilitation program, tailored on the patient’s functional condition and lasting at least one hour a day, was based on passive, active-assisted and active exercises, focused on both the upper and lower limbs, but it did not include active or active-assisted exercises with the affected hand.

Outcome measures

The MAS was used to rate muscle tone of wrist and fingers flexor muscles (primary outcome measure). The MAS rates muscle tone from 0 (no increased muscle tone) to 4 (rigid flexion or extension) [34].

The compliance of patients was assessed in terms of active participation using the Pittsburgh Rehabilitation Participation Scale (PRPS), which is reliable and valid measure of inpatients’ participation in rehabilitation sessions. Participation is scored from 1 (refusal or no participation in any session) to 6 (excellent participation) [28].

The motor section of the Fugl-Meyer Assessment Upper Extremity (FMA-UE) was used to assess the motor function of the upper limb. The motor section of FMA-UE evaluates aspects of movement, reflex, coordination, and speed. Each domain contains multiple items, each scored on a 3-point ordinal scale (0 = cannot perform, 1 = performs partially, 2 = performs fully). The motor section of FMA-UE is scored out of 66, with sub-scores of 24 for the wrist and hand [35].

The Medical Research Council (MRC) scale for strength was used to rate muscle strength of wrist and fingers flexor and extensor muscles (0 = no contraction; 5 = normal strength).

EMG assessment and measurement

Surface EMG from flexor muscles of the wrist and fingers was used to assess spasticity and spastic dystonia (secondary outcome measure). Surface pre-amplified electrodes with fixed inter-electrode distance of 20 mm (TSD150B, Biopac Systems Inc, USA) were placed over the muscle belly of Flexor Carpi Radialis (FCR) and Flexor Digitorum Superficialis (FDS) of the affected side, according to SENIAM guidelines [36]. Wrist joint angles were monitored by an electronic goniometer placed across the wrist joint (TSD130B, Biopac Systems Inc, USA). All signals were acquired by a Biopac MP100 unit (Biopac Systems Inc, USA) with a 2-KHz sampling rate. A Blackman-61 dB 10–350 Hz band-pass filter was used for offline processing (AcqKnowledge 3.8.1 software; Biopac Systems Inc, USA).

Subjects were seated in a chair with their back supported. For the entire duration of the recording session, subjects were instructed to stay completely relaxed and in silence. In each recording session, 5 EMG trials were collected. Each EMG trial included the following 3 subsequent phases. Phase 1: spastic dystonia (SD). Subject’s arms were arranged over his/her lap in the most natural position. EMG signal was recorded for approximately 10 seconds (s). Phase 2: dynamic stretch reflex (DSR). The examiner (CT, medical doctor) grasped the subject's fingers and moved them and the wrist from the natural position of

phase 1 to maximal extension in 1 s. Phase 3: static stretch reflex (SSR). After the dynamic phase of the stretch, the subject's wrist and fingers were kept in the extended position for approximately 10 s. To control the duration of the passive displacement, a method developed in our laboratory was used [37].

The times corresponding to stretch onset and termination were visually detected on the goniometer trace displayed on the computer screen, using a display gain of 20°/cm and a temporal window of 340 ms/cm. The Average Rectified Values (ARVs) of SD, DSR and SSR were calculated using the dedicated AcqKnowledge analysis software (Biopac Systems).

Time course

Clinical outcomes and stretch reflex were assessed at the beginning of the treatment (T0), at the end of the treatment (T1), 10 days after the end of the treatment (T2) and one year after stroke (T3).

Declarations

Acknowledgements

This work was supported in part by the EU ERC Synergy program under Grant No. 810346 (Natural BionicS).

The authors would like to acknowledge the helpful feedback of prof. Dario Farina. Moreover, the authors thank Manuel Barbarossa, Mattia Poggiani, Vinicio Tincani, Cristiano Petrocelli, for their help in the design and production of the SoftHand-X.

Author contributions

Conceptualization: AB, CT; Data curation: AC, MR, LP; Formal Analysis: CT, LP, LM; Funding acquisition: AB; Investigation: LP, AF, MP, MR, AC; Methodology: CT, MGC, GG, LM, AB; Project administration: CT, AB; Resources: AB, CT; Software and Hardware: MGC, GG, MR, AC; Supervision: MGC, GG, AB, CT; Visualization: AC, GG; Writing – original draft: CT, LM, AB, AC; Writing – review & editing: GG, CT

Data availability

All data are available in the main text or the supplementary materials.

Competing interests (mandatory)

MGC is one of the founders and shareholders of qrobotics s.r.l., a company that produces and commercializes soft robotic hands similar to those used in this investigation.

GG is one of the founders and shareholders of qrobotics s.r.l., a company that produces and commercializes soft robotic hands similar to those used in this investigation.

AB is one of the founders and shareholders of qbrobotics s.r.l., a company that produces and commercializes soft robotic hands similar to those used in this investigation.

References

1. Carolei, A., Sacco, S., Santis, F. D. & Marini, C. Epidemiology of Stroke. Clin. Exp. Hypertens. **24**, 479–483 (2002).
2. Kwakkel, G., Kollen, B. J., van der Grond, J. & Prevo, A. J. H. Probability of regaining dexterity in the flaccid upper limb: impact of severity of paresis and time since onset in acute stroke. Stroke **34**, 2181–2186 (2003).
3. Naess, H., Waje-Andreassen, U., Thomassen, L., Nyland, H. & Myhr, K.-M. Health-Related Quality of Life Among Young Adults With Ischemic Stroke on Long-Term Follow-Up. Stroke **37**, 1232–1236 (2006).
4. Pathophysiology of Stroke Rehabilitation: The Natural Course of Clinical Recovery, Use-Dependent Plasticity and Rehabilitative Outcome - Abstract - Cerebrovascular Diseases 2007, Vol. 23, No. 4 - Karger Publishers. <https://www.karger.com/Article/Abstract/98323>.
5. Langhorne, P., Coupar, F. & Pollock, A. Motor recovery after stroke: a systematic review. Lancet Neurol. **8**, 741–754 (2009).
6. Langhorne, P., Bernhardt, J. & Kwakkel, G. Stroke rehabilitation. Lancet Lond. Engl. **377**, 1693–1702 (2011).
7. Buma, F., Kwakkel, G. & Ramsey, N. Understanding upper limb recovery after stroke. Restor. Neurol. Neurosci. **31**, 707–722 (2013).
8. Song, G. B. The effects of task-oriented versus repetitive bilateral arm training on upper limb function and activities of daily living in stroke patients. J. Phys. Ther. Sci. **27**, 1353–1355 (2015).
9. Good, D. C., Bettermann, K. & Reichwein, R. K. Stroke Rehabilitation. Contin. Lifelong Learn. Neurol. **17**, 545 (2011).
10. Dietz, V., Quintern, J. & Berger, W. Electrophysiological studies of gait in spasticity and rigidity. Evidence that altered mechanical properties of muscle contribute to hypertonia. Brain **104**, 431–449 (1981).
11. THILMANN, A. F., FELLOWS, S. J. & GARMS, E. THE MECHANISM OF SPASTIC MUSCLE HYPERTONUS: VARIATION IN REFLEX GAIN OVER THE TIME COURSE OF SPASTICITY. Brain **114A**, 233–244 (1991).
12. Trompetto, C. *et al.* Spastic dystonia in stroke subjects: prevalence and features of the neglected phenomenon of the upper motor neuron syndrome. Clin. Neurophysiol. **130**, 521–527 (2019).
13. Trompetto, C. *et al.* Pathophysiology of Spasticity: Implications for Neurorehabilitation. *BioMed Res. Int.* 2014, e354906 (2014).
14. Opheim, A., Danielsson, A., Alt Murphy, M., Persson, H. C. & Sunnerhagen, K. S. Upper-limb spasticity during the first year after stroke: stroke arm longitudinal study at the University of Gothenburg. Am. J.

- Phys. Med. Rehabil. **93**, 884–896 (2014).
15. Sunnerhagen, K. S., Opheim, A. & Alt Murphy, M. Onset, time course and prediction of spasticity after stroke or traumatic brain injury. *Ann. Phys. Rehabil. Med.* **62**, 431–434 (2019).
 16. Laidler, P. The cause for concern. in *Stroke Rehabilitation: Structure and Strategy* (ed. Laidler, P.) 7–18 (Springer US, 1994). doi:10.1007/978-1-4899-3470-3_2.
 17. Qian, Q. *et al.* Early Stroke Rehabilitation of the Upper Limb Assisted with an Electromyography-Driven Neuromuscular Electrical Stimulation-Robotic Arm. *Front. Neurol.* **8**, (2017).
 18. Pollock, A. *et al.* Interventions for improving upper limb function after stroke. *Cochrane Database Syst. Rev.* CD010820 (2014) doi:10.1002/14651858.CD010820.pub2.
 19. Veerbeek, J. M., Langbroek-Amersfoort, A. C., van Wegen, E. E. H., Meskers, C. G. M. & Kwakkel, G. Effects of Robot-Assisted Therapy for the Upper Limb After Stroke. *Neurorehabil. Neural Repair* **31**, 107–121 (2017).
 20. Llorens - Bonilla, B., Parietti, F. & Asada, H. H. Demonstration-based control of supernumerary robotic limbs. in *2012 IEEE/RSJ International Conference on Intelligent Robots and Systems* 3936–3942 (2012). doi:10.1109/IROS.2012.6386055.
 21. Parietti, F. & Asada, H. H. Independent, voluntary control of extra robotic limbs. in *2017 IEEE International Conference on Robotics and Automation (ICRA)* 5954–5961 (2017). doi:10.1109/ICRA.2017.7989702.
 22. Salvietti, G. *et al.* Compensating Hand Function in Chronic Stroke Patients Through the Robotic Sixth Finger. *IEEE Trans. Neural Syst. Rehabil. Eng.* **25**, 142–150 (2017).
 23. Ciullo, A. S. *et al.* A Novel Soft Robotic Supernumerary Hand for Severely Affected Stroke Patients. *IEEE Trans. Neural Syst. Rehabil. Eng.* **28**, 1168–1177 (2020).
 24. Deconinck, F. J. A. *et al.* Reflections on Mirror Therapy: A Systematic Review of the Effect of Mirror Visual Feedback on the Brain. *Neurorehabil. Neural Repair* **29**, 349–361 (2015).
 25. Gandhi, D. B., Sterba, A., Khatter, H. & Pandian, J. D. Mirror Therapy in Stroke Rehabilitation: Current Perspectives. *Ther. Clin. Risk Manag.* **16**, 75–85 (2020).
 26. Laver, K. E. *et al.* Virtual reality for stroke rehabilitation. *Cochrane Database Syst. Rev.* (2017) doi:10.1002/14651858.CD008349.pub4.
 27. Miclaus, R. *et al.* Non-Immersive Virtual Reality for Post-Stroke Upper Extremity Rehabilitation: A Small Cohort Randomized Trial. *Brain Sci.* **10**, 655 (2020).
 28. Lenze, E. J. *et al.* The Pittsburgh Rehabilitation Participation Scale: reliability and validity of a clinician-rated measure of participation in acute rehabilitation. *Arch. Phys. Med. Rehabil.* **85**, 380–384 (2004).
 29. Godfrey, S. B. *et al.* The SoftHand Pro: Functional evaluation of a novel, flexible, and robust myoelectric prosthesis. *PLOS ONE* **13**, e0205653 (2018).
 30. Bicchi, A., Gabbicini, M. & Santello, M. Modelling natural and artificial hands with synergies. *Philos. Trans. R. Soc. B Biol. Sci.* **366**, 3153–3161 (2011).

31. Postural Hand Synergies for Tool Use | Journal of Neuroscience.
<https://www.jneurosci.org/content/18/23/10105.short>.
32. Feldman, A. G. Once More on the Equilibrium-Point Hypothesis (λ Model) for Motor Control. *J. Mot. Behav.* **18**, 17–54 (1986).
33. Capsi-Morales P., Piazza C., Catalano M.G., Bicchi A., & Grioli G. Exploring Stiffness Modulation in Prosthetic Hands and Its Perceived Function in Manipulation and Social Interaction. *Front. Neurorobotics* **14**, (2020).
34. Bohannon, R. W. & Smith, M. B. Interrater reliability of a modified Ashworth scale of muscle spasticity. *Phys. Ther.* **67**, 206–207 (1987).
35. Fugl-Meyer, A. R., Jääskö, L., Leyman, I., Olsson, S. & Steglind, S. The post-stroke hemiplegic patient. 1. a method for evaluation of physical performance. *Scand. J. Rehabil. Med.* **7**, 13–31 (1975).
36. Hermens, H. J. *et al.* European Recommendations for Surface ElectroMyoGraphy. 4.
37. Marinelli, L. *et al.* Manual Linear Movements to Assess Spasticity in a Clinical Setting. *PLOS ONE* **8**, e53627 (2013).

Figures

Figure 1

Rehabilitation setup. (A) SoftHandX Supernumerary Robotic Hand and its main subsystems, including the hand hardware and the sensing system used to convert motions of the patient into motions of the robot. (B) Photographic sequence of the motion pattern of the supernumerary robotic hand, inspired to the most statistically frequent human hand motion, described in literature as the first postural synergy of grasping. (C) Grip patterns of the soft supernumerary robotic hand conforming to the shape of different

objects to achieve a natural-looking grasp posture. (D) Illustration of the full rehabilitation scenario: a patient (white) is sat comfortably and wears the supernumerary limb (red); a therapist (green) guides the patient in the manipulation of objects (blue) resting on a table. (E) Close-up picture of one of the rehabilitation phases: the patient must reach a plastic cube placed on the table, grab it, and then release it. The physiotherapist supports the arm and forearm, facilitating the patient's proximal movements. The grip and release movements are performed through the robotic hand under patient's control, without the help of the physiotherapist.

DSR with or without SSR) was present in all 4 patients at T0 in both FCR and FDS, with the exception of patient 3, in whom spasticity was present only in FCR. After treatment (T1), spasticity disappears in patients 1, 2, 4 and decreases in patient 3.