Do Shape Memory Alloys Represent A New Frontier in Neurorehabilitation?

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Abstract

Following to their nonlinear properties, shape memory alloys (SMAs) are a very promising class of metallic materials. In particular base on pseudo-elasticity behavior, shape memory effect and damping capacity, SMA have been recently applied in the field of neuromuscular rehabilitation, designing some new devices based on the above properties. The paper reports about possible uses of these materials in the treatment of movement disorders, such as dystonia or hyperkinesia, where their dynamic characteristics can be the key issue.

Keywords: Shape memory alloys; Phase transformation; Properties; Pseudo-elasticity; Neurology

Introduction

Shape memory alloys (SMAs) represent a unique materials family due to their ability to recover the original form after deformation by heating. Shape memory alloys are characterized by two stable metal phases: austenite and martensite. Austenite phase is stable at high temperature while martensite is stable at low temperature. During the heating stage, microstructure transforms from martensite to austenite. Vice-versa on cooling. This feature is responsible of SMA super-elasticity. This is exactly what is needed for a lot of possible applications. The use of SMAs has increasingly expanded in recent decades [1-5]. This also makes great difference with respect to more traditional Al alloys. Many scientists have intensively been involved in research projects aimed at developing innovative devices and exploring new possible applications, making therefore the use of these smart materials e reality. Indeed, the number of commercial applications is growing each year, with the largest application segment of the market represented by actuators and motors. SMAs show physical and mechanical features that made them successful candidates for use in structural engineering applications [6-9] and in nuclear ones [10].

Up to know, SMAs played a key role in the development and implementation of smart materials/devices, which can be integrated into structures to provide functions such as sensing, energy dissipation, actuation, monitoring, self-adapting, and healing of structures. In recent decades, intensive research efforts have been concentrated in the field of structural engineering, aiming at employing smart engineered systems in civil engineering applications, with emphasis to seismic response control of structures also in partial substitution of most commonly used steel materials [11-15]. Another major growth driver for the shape memory alloy has also been the boom in the medical sector and in general in the health sector, using shape memory alloy in dental, orthopedics, neural, vascular and surgical fields. This mainly follows its good biocompatibility, excellent magnetic resonance and Computer Tomography (CT) compatibility. This was also favored by an increasing use of Additive Manufacturing (3D printing) processes applied to metallic materials [16-17] with consequent customization of the component. It has also to be taken into account that SMAs can be nowadays 3D-printed: up to know on the contrary only few Al alloys grades can be printed.

This make a strong advantage for such class of materials in terms of patient’s customization. As a matter of fact, the use of conventional materials strongly limits in terms of versatility because material properties are fixed and do not adapt to the dynamic changes in patient’s clinical needs or disorder evolutions. Materials with unusual and non-linear properties, on the other hand, can offer possible alternatives to standard ones [18-21]. A satisfactory balance between deformability, strength, weight and reliability gives the SMA materials the right characteristics to be employed in the physical rehabilitation field. Among the several properties of SMA, pseudo-elasticity and the shape memory effect are the most useful in neurology and neuromuscular rehabilitation applications: in particular, stable (quasi-constant stress levels) and long (large deformability ranges) plateau and also the possibility...
to modify those parameters with thermomechanical treatments can be exploited in designing a variety of devices and solutions for rehabilitation; also the internal friction and mechanical hysteresis characteristics show allows such materials to be used for such applications. The SMAs phenomenology is reported in detail in [22].

We here just report some application in neurorehabilitation aimed to show the feasibility and relevant outcomes and open the question: can really such materials represent a new frontier in neuro-rehabilitation, also considering the strong recent development of additive manufacturing technology? Our opinion is yes, they do.

Some Applications of SMAS in Neurorehabilitation

Portable Devices for Passive and Aided Exercise

The physical rehabilitation of patients suffering from paresis following neurological insult is usually based on active exercise. Although it is well known that active exercise is quite important for the re-acquisition of motor skills, limbs passive mobilization is also a standard part of physical treatment. This is due to the fact that it can help in safeguarding tissues viscoelastic properties in otherwise disused muscles and joints. This approach is particularly important in the sub-acute period following the neural trauma. In fact, in that phase, paresis itself precludes the active work-out of the patient. In addition to this, it can be imagined that a repetitive mobilization of the affected segments could help maintain viable a network of neuronal circuitry that is involved in movement planning and execution, at least by continually providing proprioceptive information and avoiding deafferentation.

In this framework a portable mobiliser for the ankle joint is has been developed. Portability was the fundamental requirement in order to make this device truly available to patients in the acute phase, because they are often bedridden and sometimes cannot even sit upright. The system is suitable to be utilized by patients sitting on or lying in bed. The concept was implemented using SMA actuation, because it allows compactness and low weight. For reasons related to the possibility of affecting the central effects of the therapy administered through this device, it was also of interest that the actuator should emit limited electromagnetic noise, in order not to affect electroencephalographic (EEG) measurements. This is also possible using SMA-based technology.

Compliant Orthoses for Limb Repositioning

Spastic syndromes, are characterized by paresis, stiffness, involuntary phasic contractions and jerks of the limbs and, depending on the affected joint, unnatural flexion or extension. Immobility and disuse of the affected joints tend to have adverse consequences, in that holding a static position for a long time can determine a shortening of the muscles and a worsening of contractures and spastic reflexes. Orthotic devices can be used to stretch muscles affected by this malformation to restore a more physiological neutral posture and increase usable joint range of motion. In the practice of standard orthotics, devices are used to hold the affected joint in a fixed position that is closer to the desired one, and muscles are expected to regain in time a more physiological length. The target position can also be changed in a stepwise manner by modifying the orthosis in order to proceed with the treatment. “Dynamic” orthoses are different because they aim at producing muscular remodeling by imposing forces or torques that pull in the desired direction. The target position is not fixed a priori, but it is the result of a dynamic balance between the pulling force of the muscles affected by contracture and the force offered by the orthosis.

This behavior is much more physiological, because residual movements of the limbs are potentially preserved, and involuntary postural changes are allowed by the device compliance, thus increasing the general comfort. What is truly important is that, thanks to orthosis compliance, immobility and disuse are avoided and so is a major cause of the known negative chronic sequelae of paresis. Under the action of the corrective torque, the muscular lengthening process generally occurs in a slow and gradual manner: in this respect, therefore, the term “dynamic” must be interpreted just to mean the opposite of “fixed” or “static”. In order to implement these concepts, a set of hinges has been recently reported [23] that can be used to create compliant orthoses. Inside the hinges two springs made of NiTi are placed, shaped as a capital letter omega (Ω) (Figure 1).

![Figure 1: Examples of Pseudo-Elastic Orthoses.](image)

This specific shape allows the material to be loaded along its entire length, prevents localized stress concentrations and failure. The spring action is based on pseudo-elasticity. The nonlinearity and hysteretic behavior of NiTi-based alloys indeed endow these orthoses with convenient characteristics for this application and solve some inherent problems of dynamic splints with purely elastic elements. In fact, in classic elastic tension or torque elements, the spring-back forces change with elongation; assuming that those elements are preloaded in such a manner as to guide repositioning towards a desired posture, the corrective force applied to the limb will be high at the beginning of the process and will gradually decrease the closer the joint angle gets to the target. Clockwork springs could be used to counter this effect, but they tend to be either weak or bulky. On the contrary, the nonlinear behavior of pseudo-elastic SMA, due to the presence of long plateau at quasi-constant stress, makes it possible to administer a continual therapeutic action even in proximity of the goal and in general for much wider deformation/elongation ranges.
By selecting appropriate thermo-mechanical treatments for the phase of shape setting, it is possible to obtain springs with different plateau stresses and lengths (deformability), and in this manner, alloy properties can be adjusted for different patients’ needs (Figure 2).

Hence, the following can be obtained simultaneously:

- providing a corrective push that is correlated to the biomechanical, biometric and clinical state of the patients, as well as to the likelihood that they will tolerate a given treatment intensity;
- maximizing acceptability and adherence to prescription times by making the corrective push mild enough and the orthosis sufficiently compliant to involuntary jerks that the pain induced by lengthening on spastic muscles is reduced;
- avoiding limb fixity, thus improving joint mobility and the chances of a residual use of the limb;
- avoiding the need to adjust spring preload as posture evolves and the associated burden for caregivers; self-regulating the strength of the orthotic action in relation to the direction of movement; thanks to SMA hysteresis, the stress during loading is higher than during unloading, so the perceived spring stiffness is higher for actions that are directed against the clinical goal.

**Tunability and Optimization of Characteristics**

The properties of SMA are tunable, i.e., by changing alloy composition or applying suitable thermo-mechanical treatments, material characteristics, such as the transformation temperatures, the height and length of the stress plateau, and to some extent, the hysteresis, the cycling stability, the internal friction, etc., can be adjusted to the final application. This opportunity offered by SMA can be exploited to modify material behavior and meet specific clinical requests, as well as the needs of the one patient for whom a certain therapeutic device is made. Some studies reported in the open literature took full advantage of that possibility, by customizing each single device to patients’ characteristics, such as age, severity, affected joint, tolerance, pain, etc. Let us consider a wearable device application, like an orthosis: in practical terms, it can be imagined that a certain number of optimized processes can be utilized to produce SMA elements with as many different final properties, each of which may be suitable for a sub-group of patients with a set combination of the mentioned characteristics (age range, severity range, etc.). In this manner, ad hoc devices could be prescribed for each sub-group, thus improving tolerability and outcomes.

**Conclusion**

The non-linear and easily adjustable characteristics of SMA make this class of materials a very interesting resource in the development of new devices and new therapies for neurologic conditions. This paper reported several applications, in which SMA provides added functionality, allows customization and improves tolerability and outcomes in clinical management of patients. The properties of SMA could help also in the design of alternative therapies for otherwise untreatable movement disorders.

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