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A Novel Soft Actuator using Metal Hydride Materials and Its Applications in Quality-of-Life Technology

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1. Introduction

Globally, social needs for daily life support systems and robots have strongly increased in an aging society with a falling birth rate. Quality-of-life technologies affect people in various settings with different needs (Cooper, 2008). To provide force and motion for rehabilitation therapy or human power assistance in quality-of-life technologies, some kinds of force devices such as electric motors, hydraulic actuators, and pneumatic actuators are used in rehabilitation apparatuses and assistive systems (Guizzo & Goldstein, 2005). It is particularly important that the force devices used for rehabilitation apparatuses or power assist systems include human-compatible softness for safety (Bicchi & Tonietti, 2004), noiselessness, and a high power-to-weight ratio.

To fulfill the above demands, we designed a novel actuator using a metal hydride (MH) alloy based on rare-earth metal compounds for a source of mechanical power. A force device using an MH alloy, which is called an MH actuator, generates a high output force, even if its size is small (Sasaki et al., 1986). The main reason is simply that the MH alloy can store a large amount of hydrogen by controlling heat energy. Moreover, the MH actuator has human-friendly flexibility and noiselessness based on a soft drive mechanism derived from the chemical reaction of metal hydrides. As you know, hydrogen is also the ideal clean energy carrier candidate because it does not have adverse effects on the environment (Sakintuna et. al., 2007).

The purpose of this chapter is threefold: (a) to outline the properties of metal hydride materials and the structure and drive mechanism of the MH actuator, (b) to describe the characteristics of a newly developed wearable MH actuator using a soft bellows made of a multilayer laminate film, which is more human-friendly than a current commercial actuator, and (c) to show some applications of the MH actuator in quality-of-life technology: a transfer aid for a wheelchair user, a continuous passive motion (CPM) machine for joint rehabilitation, and a power assist system for bed sore prevention of people with restricted mobility. Further, we describe a subsystem component to convert from hydrogen gas pressure to air pressure to facilitate safety and versatility of the MH actuator.

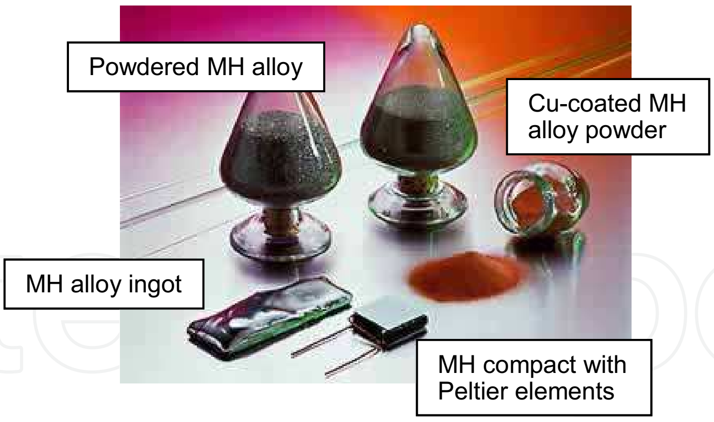

Fig. 1. Various forms of a metal hydride alloy (ingot, powder, Cu-coated powder, and compact module nipped Peltier modules) to embed in the MH actuator.

Finally, we will discuss some issues to improve the MH actuator for more suitable devices in assistive technology and rehabilitation engineering.

2. Metal Hydride Actuator

2.1 Metal Hydride Materials

MH alloys are particular materials that have the ability to store a large amount of hydrogen, about 1000 times as large as the volume of the alloy itself. The various forms of the MH alloy are shown in Fig. 1. One of the conventional metal hydride materials is Mg_2Ni, which was discovered in 1968 at Brookhaven National Laboratory, USA (Wiswall & Reilily, 1974). This is historically the first practical metal hydride material. Shortly thereafter, as it happens, $LaNi_5$ was discovered in 1970 at Philips Research Laboratories, the Netherlands (Van Mal et al., 1974). These successive discoveries became a trigger of research of various MH alloys and opened new possibilities for industrial developments.
A reversible chemical reaction between metal (M) and hydrogen gas (H_2) generates metal hydrides (MH_x) as in the following reaction formula:

$$\mathrm{M} + \frac{x}{2}\mathrm{H}_2 \leftrightarrow \mathrm{MH}_x + Q \quad (1)$$

where Q is the heat of reaction, and thus, $Q > 0$ J/mol for H_2. If this reaction succeeds at a fixed temperature, then it will advance up to an equilibrium pressure, which is the plateau pressure. The PCT diagram (P: hydrogen pressure, C: hydrogen content, T: temperature) shows the basic characteristics of the MH alloy. As demonstrated in the PCT diagram in Fig. 2, changing the temperature of the MH alloy can control the plateau pressure. The MH alloy with a good hydrogen absorbing property for actuator applications has a flat and wide plateau area in the PCT diagram.

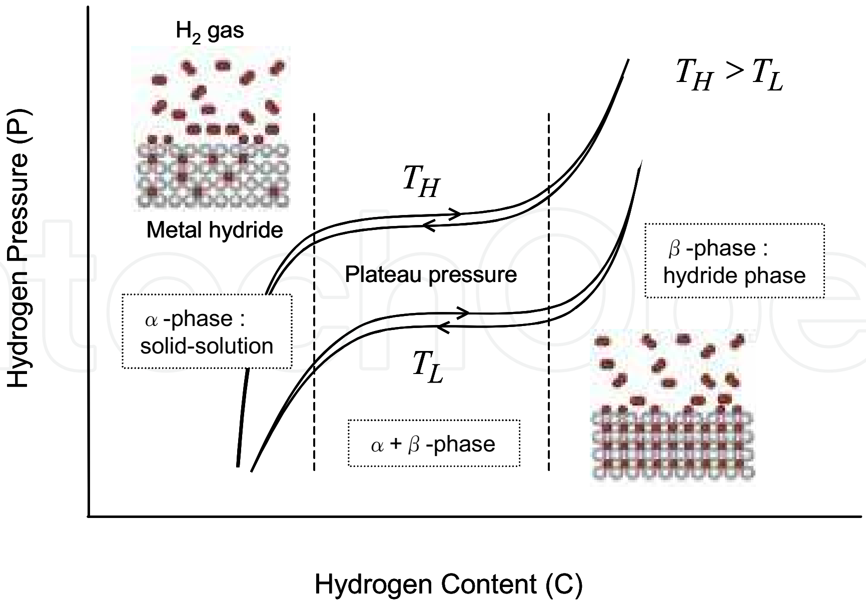

Fig. 2. Pressure-content-temperature plot (PCT diagram) of a metal hydride alloy.

Then, the hydrogen equilibrium pressure (*P*) is related to the changes *ΔH* and *ΔS* in enthalpy and entropy, respectively, as a function of temperature (*T*) by the Van't Hoff equation:

$$\log_e P = \frac{\Delta H}{\mathrm{R}} \cdot \frac{1}{T} - \frac{\Delta S}{\mathrm{R}} \tag{2}$$

where R is the gas constant. The PT diagram of a CaNi based alloy is shown in Fig. 3. The relationship between the hydrogen equilibrium pressure and the temperature of the $CaNi_5$ alloy can be partially adjusted by changing the alloy's composition with the addition of mishmetal (Mm) and aluminum (Al). Mishmetal is a common name for a mixture of unrefined rare earth elements.

Furthermore, the MH alloy is not combustible or flammable, so it is safe as a hydrogen storage material for a fuel cell in road vehicles and other mobile applications (Schlapbach & Züttel, 2001).

2.2 Fundamental Mechanism and Configuration

Not only can the MH alloy efficiently store a large amount of hydrogen gas, it also desorbs hydrogen gas by controlling its own temperature. If the reversible reaction is carried out in a hermetically closed container system, heat energy applied to the MH alloy is converted into mechanical energy via a pressure change in the container system, as shown in Fig. 4. Thus, the MH actuator functions by using the hydrogen gas pressure derived from the MH alloy through the heat energy, which is controlled by a thermoelectric Peltier device for heating and cooling force.

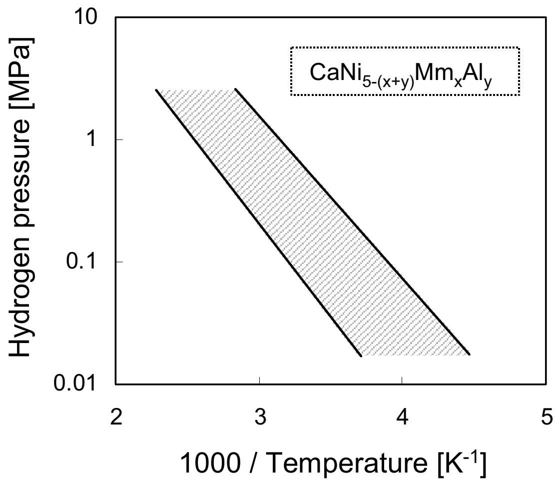

Fig. 3. Relationship between equilibrium hydrogen pressure and temperature (PT diagram) in $CaNi_5$ based MH alloys.

The MH actuator is composed of a solidified MH alloy powder, Peltier elements to electrically control the temperature of the alloy, an MH container to act as a small gas cylinder, and an end-effecter to transfer the hydrogen gas pressure into an acting force (Ino et al., 1992).

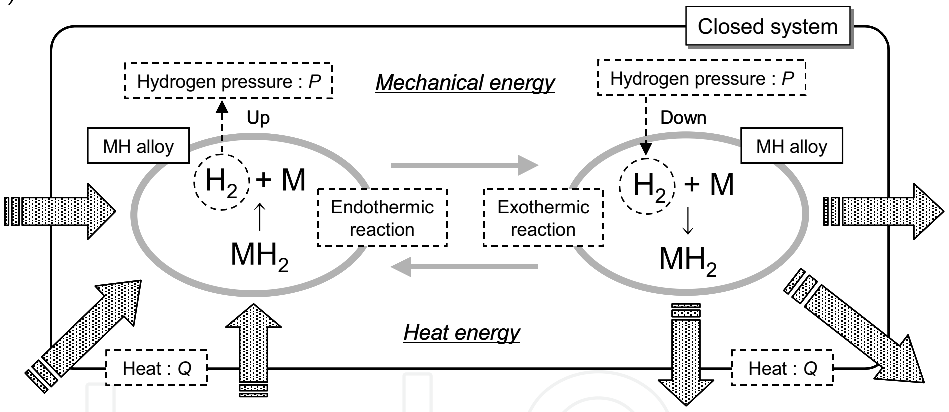

Fig. 4. Schematic illustration of actuation principles based on an energy conversion mechanism between heat, *Q*, and hydrogen pressure, *P*, in a MH actuator system.

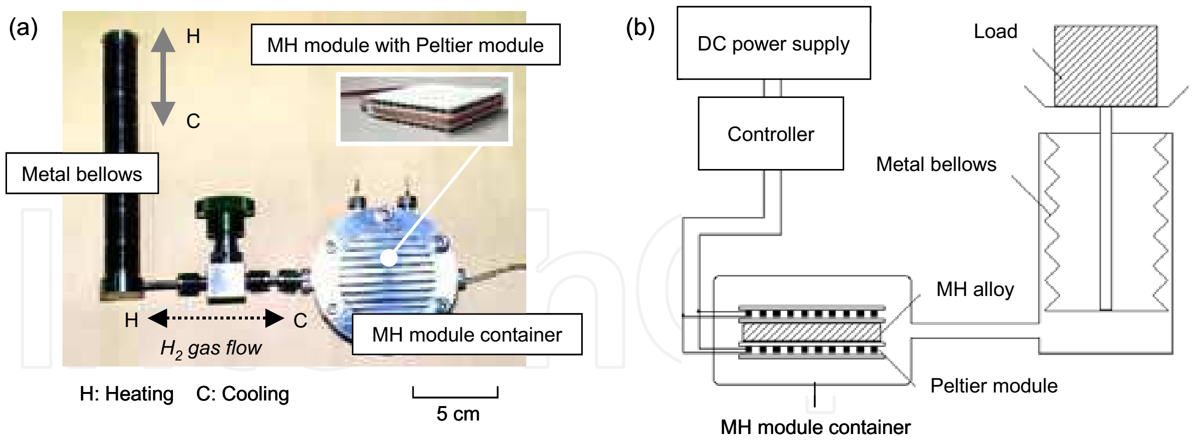

Fig. 5. Photograph of an MH actuator using a metal bellows (left) and a block diagram of an MH actuator system (right).

For example, the MH actuator shown in Fig. 5 contains six grams of an MH alloy. The maximum output force of this actuator is approximately 100 N. The power-to-weight ratio of the MH actuator is very high compared to those of traditional actuators, such as an electric motor and a hydraulic actuator (Wakisaka et al., 1997). However, the MH actuator uses the Peltier device, so it is not as energy efficient as an electric actuator. On the other hand, the heat drive mechanism of the MH actuator does not produce any noise or vibration. In addition, the reversible hydrogen absorption/desorption also has a buffering effect to act as a cushion to a human body and prevents extreme power surges or shock loads. Therefore, the MH actuator is suitable for use as a human-sized flexible actuator applied to soft and noiseless rehabilitation systems and assistive devices.

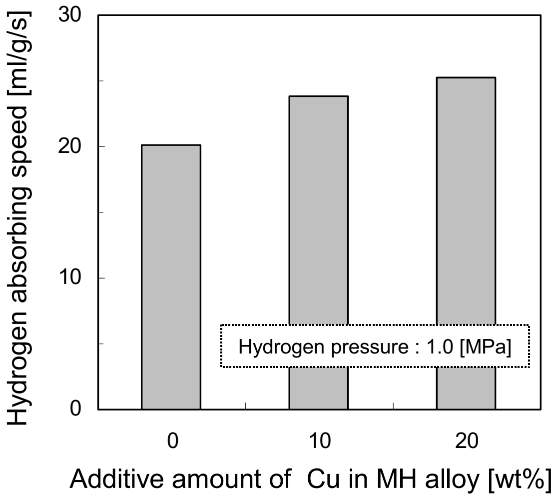

Fig. 6. Hydrogen absorbing speed versus additive amount of copper in the MH alloy powder at 1.0 MPa.

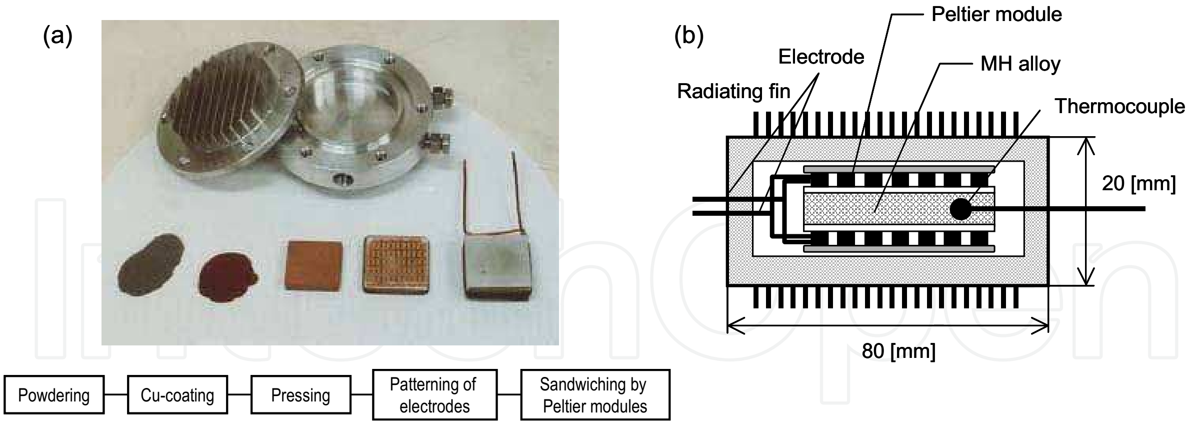

Fig. 7. Processing of the HM module components to improve heat conductivity for the acceleration of hydrogen absorbing speed of the MH alloy (left) and a cross-section of the MH module container (right).

3. Improvement on Metal Hydride Alloy

3.1 Heat Conductivity

The MH actuator has some unique properties such as a high power-to-weight ratio, lightweight, no noise, and softness. However, the speed of motion is relatively slow because the drive mechanism of the MH actuator depends on the poor heat conductivity of an activated MH alloy.

We designed the MH alloy to be powdered to improve the heat conductivity of the activated MH alloy, and this powdered MH alloy was coated with copper by chemical plating. The heat conductivity was increased about 50 times over that of only an MH alloy. As the results show in Fig. 6, the addition of Cu yields a clear increase in the hydrogen absorption speed.

From the experimental results, the powdered MH alloy was coated with a 1.0-μm-thick Cu (20 wt%). The MH alloy powder was solidified into a compact MH by pressing it to a thickness of about 3.0 mm. The heat source using a Peltier element was directly attached to the MH alloy compact to build in an integrated module. To assemble the Peltier element into this integrated module, the surface of the MH alloy compact was coated with alumina (Al_2O_3), which is an electric insulator, by plasma spraying, and the circuit pattern of the Peltier element was drawn on the alumina coating layer. These components of an MH module for the MH actuator are shown in Fig. 7 (a). The cross section of the MH module and container are illustrated in Fig. 7 (b).

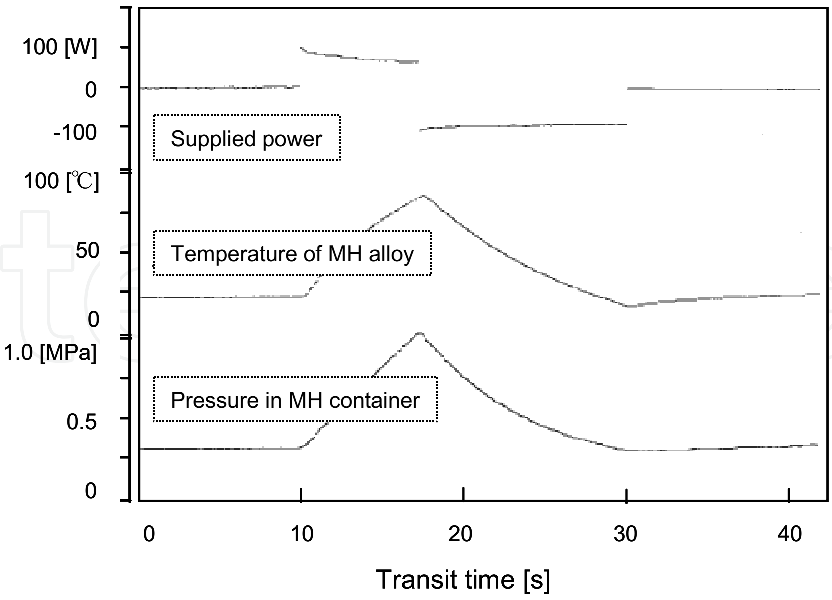

Fig. 8. Measured patterns of the pressure in the MH container and the temperature of the MH alloy with the application of a step voltage input through a DC power supply.

3.2 Motion Speed

By the improvement of the heat of conductivity of the MH module, the response speed of the MH actuator is increased, and it is potentially more useful in an actual power assist device for rehabilitation equipment.

The relationship between the temperature of the MH alloy and the pressure in the hermetically sealed container is shown in Fig. 8. The pressure rose smoothly from 0.3 to 1.0 MPa during 7.0 s. The time delay from the temperature change of the MH alloy to the pressure change of the container was about 0.1 s. Therefore, the MH actuator is sufficient for applications needing gentle motion such as joint rehabilitation or power assistance of bodily movement.

4. Design of a Soft End-Effector

4.1 Laminate Film Bellows

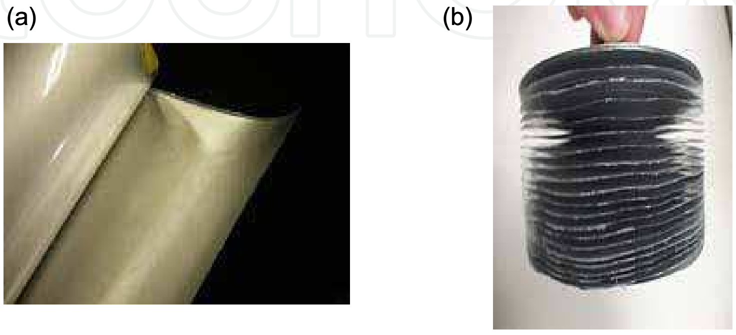

Fig. 9. Multilayer laminate film sheet (left) and a soft bellows made of the PE-Al-PET laminate film (right).

To maintain impermeability to hydrogen, a metal bellows has been used as the end-effector in conventional MH actuators. However, using stainless steel in fabricating the metal bellows has limitations in terms of weight, elongation rate, and flexibility. Rehabilitation equipment and power assist devices for human use must be light and a compatible softness with a human body. Therefore, we have attempted to develop a soft and light bellows made of non-metal materials to improve the human-friendliness of the MH actuator. The bellows of the MH actuator needs to be flexible, lightweight, and impermeable to hydrogen. However, fulfilling these conditions using only non-metal materials is very difficult. Alternatively, a polymer-metal laminate composite was selected here for a suboptimal solution (Ino et al., 2009).

The applied laminate composite is a tri-layer structure film of polyethylene (PE), aluminum (Al), and polyester (PET). The total thickness of the film is about 100 μm. The hydrogen barrier performance of the laminate film is supposed to be proportional to the thickness of the aluminum layer, but the flexibility of the film decreases as the thickness increases. These properties of the laminate film are in a trade-off relationship with the aluminum layer thickness. The aluminum layer thickness adopted in this design is 12 μm. We fabricated the laminate film bellows with a diameter of 100 mm and 20 corrugations using this laminate film, as shown in Fig. 9.

	Metal bellows	Laminate film bellows
Maxmun output [kgf]	28	28
Maxmun stroke [mm]	130	130
Weight [g]	800	35
Initial length [mm]	240	8
Withstand pressure [MPa(gauge)]	1	0.08
Section area [cm^2]	3.5	50

Table 1. Comparison between a metal bellows and a laminate film bellows in mechanical properties.

Table 1 shows a comparison between the mechanical parameters of the laminate film bellows and those of the metal bellows. The maximum force output and the maximum stroke were aligned to the same value for comparison. The weight of the laminate film bellows was 20 times lighter than that of the metal one, and the elongation range of the laminate film bellows was 30 times as large as that of the metal one. Hence, these mechanical properties of the laminate film bellows are useful to design a soft MH actuator.

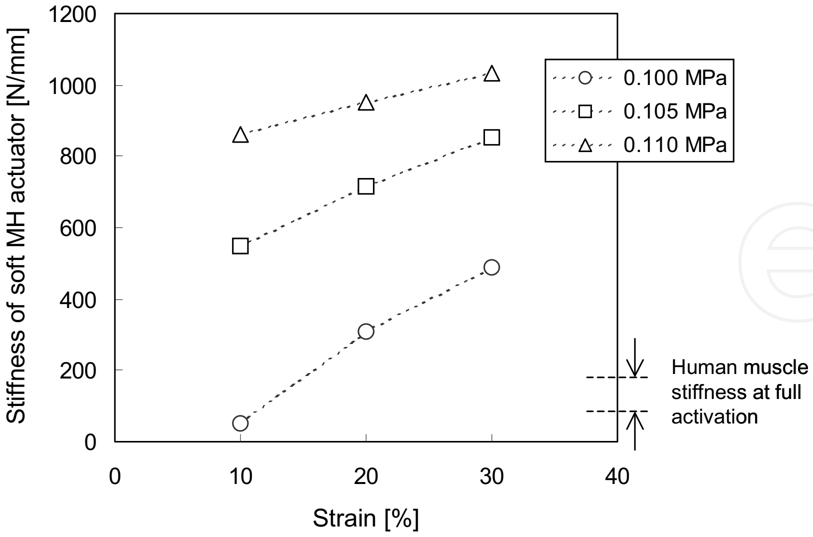

Fig. 10. Stiffness of the laminate film bellows versus applied strain changing the initial inner pressure of the MH actuator and the range of human muscle stiffness at full activation.

4.2 Hydrogen Impermeability

It is well known that a polymer-metal laminate film is a strong gas barrier to oxygen, water vapor, and other substances in the packaging industry (Schrenk & Alfrey Jr., 1969). However, data do not exist about the hydrogen impermeability of the laminate film and its adhesion area by thermo-compression bonding.

The hydrogen impermeability of the soft bellows made of the laminate film was examined by monitoring the inner pressure and displacement of the soft bellows filled with 99.99999% pure hydrogen gas. The initial inner pressure in the soft bellows was 0.02 MPa (gauge), and the water temperature of a bath to immerse the soft bellows was controlled at 20 °C.

From the experimental result, the amount of decompression of the soft bellows after 240 hours was about 0.7% of the initial inner pressure. Thus, it was clear that the laminate film bellows was capable of maintaining a hydrogen gas barrier for at least ten days.

4.3 Flex Durability

The aluminum layer of the laminate film may fracture due to metal fatigue if a bending motion is repeatedly applied for a long time period. If a fracture occurs in the laminate film, the inner pressure and stroke length of the laminate film bellows may decline rapidly. Thus, a flex durability test was performed to determine how long the laminate film bellows could continuously flex and extend.

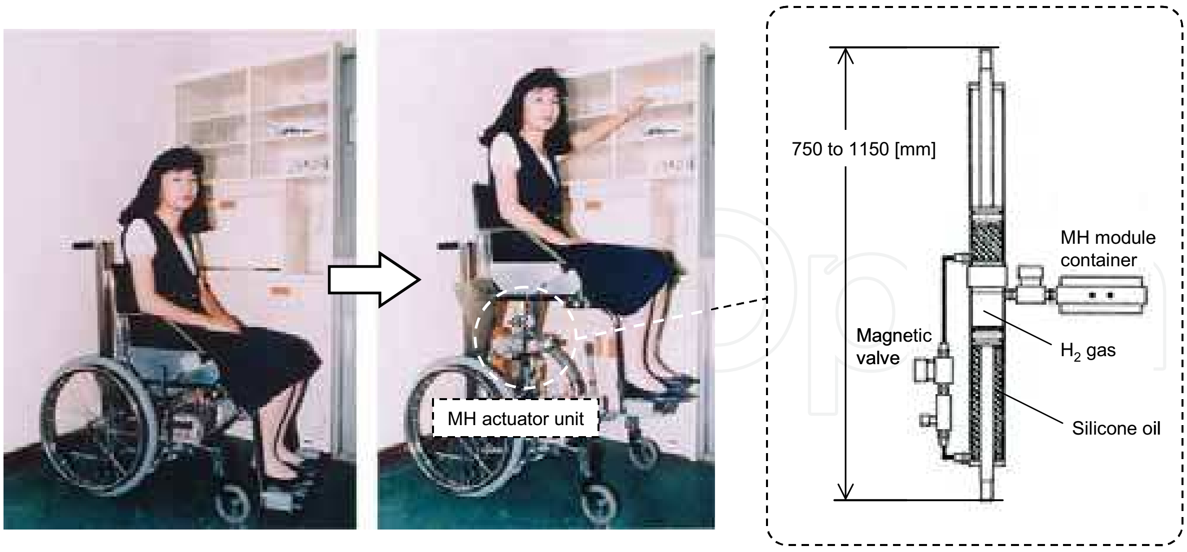

Fig. 11. Wheelchair seat lift using the MH actuator (left) and its long stroke tandem cylinder having a function that is convertible from a hydrogen gas pressure to a silicone oil one (right).

From the durability test, the laminate film did not break down by repeated motion for ten days. There was no clear change of the inner pressure and stroke length during the flex durability test, so the laminate film bellows could perform normally for more than 3,500 strokes. The number of strokes in this test should guide the assumption of a periodic replacement of this laminate film bellows, which helps maintain good hygiene.

4.4 Passive Elasticity

The passive elasticity of the soft MH actuator built in the laminate film bellows was measured by a universal tester. The relationship between the stiffness and the strain of the laminate film bellows where the parameters are the initial inner pressure (P_0 = 0.100, 0.105, and 0.110 MPa) of the MH actuator is shown in Fig. 10. It was found that the stiffness increased with increasing strain on the laminate film bellows, and that the rate of the stiffness change (gradient) decreased with increasing initial inner pressure of the soft MH actuator. The stiffness of the soft MH actuator with a closed valve was higher than that with an opened valve. This actuator property may be a result of hydrogen being absorbed by the MH alloy due to applying pressure from outside the bellows.

Moreover, the range of the variable stiffness of human muscle at full activation (Cook, C. S. & McDonagh, M. J. N., 1996) was included in that of the soft MH actuator, as shown in Fig. 10. Thus, the soft MH actuator may be suitable for a human power assist and rehabilitation device from the viewpoint of mechanical impedance matching and safety in passive elasticity to reduce any potential danger.

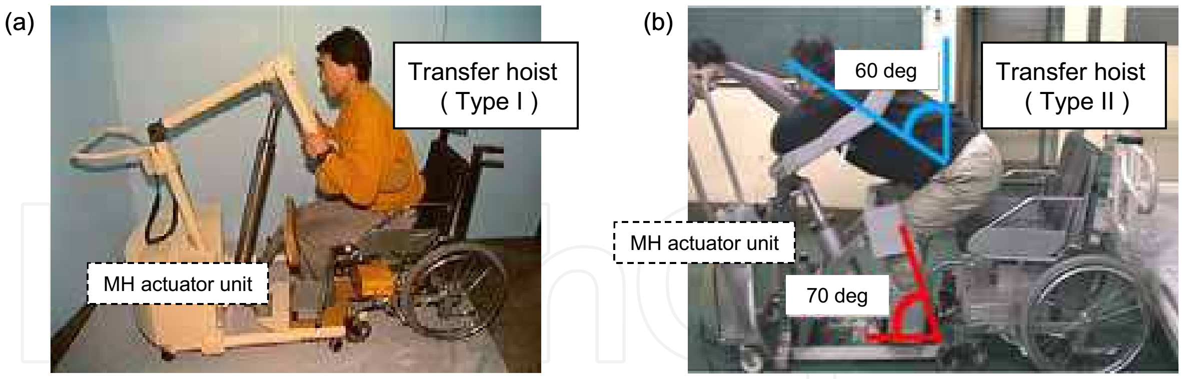

Fig. 12. Transfer hoists using a high power MH actuator unit (type I, left) and its downsized MH actuator unit with an accumulator (type II, right).

4.5 Cost-Effectiveness

The laminate bellows can be produced at very low cost compared to a metal one because a mass-produced polymer-metal laminate film is not typically expensive. Therefore, it is possible to create a disposable version of the laminate film bellows, which would satisfy the hygienic requirements of medical and rehabilitation devices.

5. Applications

5.1 Wheelchair Seat Lift

A wheelchair is a popular assistive device for persons with lower limb disability or the elderly. Recently, the wheelchair has taken significant functional advancement and many types have been developed to conform to the life style of wheelchair users. When using a wheelchair, however, some tasks meant to be performed from a standing position, such as reaching a tall shelf and cooking in the kitchen are very difficult in daily life. Thus, a wheelchair with a seat lift system using the MH actuator was developed to improve the quality of life (Wakisaka et al., 1997).

These assistive systems for human body motion need an especially long stroke displacement for lifting. Therefore, a long stroke MH actuator using a tandem piston cylinder with a solenoid valve was developed, as shown in Fig. 11. When hydrogen gas flows from the lower piston, silicone oil in the lower piston moves to the upper piston depending on the rate of flow of the hydrogen gas. By using such a drive mechanism, the stroke displacement obtained totally by an MH actuator system is doubled in comparison with an actuator drive system using only hydrogen gas. The seat height of the wheelchair can be stabilized by stopping the silicone flow via the solenoid valve.

This MH actuator, which adopts a 40-g $CaNi_5$ alloy, can produce approximately an 800 N output force and a 40 cm stroke. The lift speed was about 20 mm/s and the total weight of the seat lift equipment including the MH actuator unit and the tandem piston cylinder was about 5 kg.

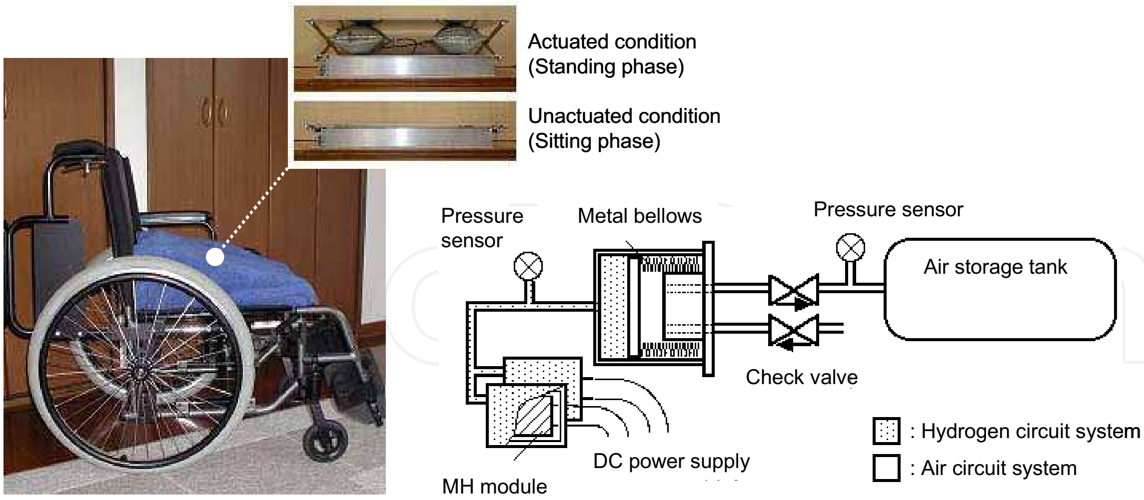

Fig. 13. Sit-to-stand assist cushion using a compact air compressor including an MH actuator unit on a wheelchair seat (left) and the schematic configuration of an MH air compressor (right).

5.2 Transfer Equipment

When people cannot stand up by themselves due to illness or injury, they need help transferring between a bed, a wheelchair, a toilet seat, a bath, etc. This transfer assistance requires a strong, safe motion. Thus, a physical and mental load exists between a patient and a helper at any time. For these reasons, we developed a transfer hoist based on an ergonomic motion analysis of transfer behavior. An MH actuator with a variable compliance function was implemented into his standing transfer hoist.

The appearance of the transfer hoist is shown in Fig. 12 (a); it has a height of 118 cm and a width of 70 cm. A kneepad, an arm pad, and a chest pad with cushioning material were built into the transfer hoist to prevent a fall with the knee flexed and to move the user's body stably and safely. These pads were designed based on the measurement of the motion analysis of elderly people (Tsuruga et al., 2001). The kneepad had a variable position mechanism using springs in consideration of changing the ankle joint angle through a transfer motion. The basic parts of the transfer hoist were a modular fashion to customize as appropriate according to the physical features of the users. We developed a double-acting MH actuator with two MH modules for the lifting mechanism of the transfer hoist. The double-acting MH actuator can control its own stiffness and position by changing the balance between the inner and outer hydrogen pressures of a metal bellows in a cylinder. This double-acting MH actuator provides a maximum lifting weight of 200 kg and a stroke of 350 mm.

The size of the transfer hoist described above is acceptable in a hospital and an assisted-living facility. However, the size is somewhat large for at home use. Thus, we redesigned a compact transfer hoist as shown in Fig. 12 (b). The MH actuator was modified to a single-acting-type mechanism using an accumulator for a reduction in size and weight. This single-acting-type MH actuator can smoothly push up and down a transfer hoist arm by use of an accumulator pressure regardless of a single MH module as well as the double-acting-type MH actuator. From this improvement, the size of the transfer hoist was a height of 80 cm and width of 45 cm, and the total weight was reduced 40% compared with the former transfer hoist (type I).

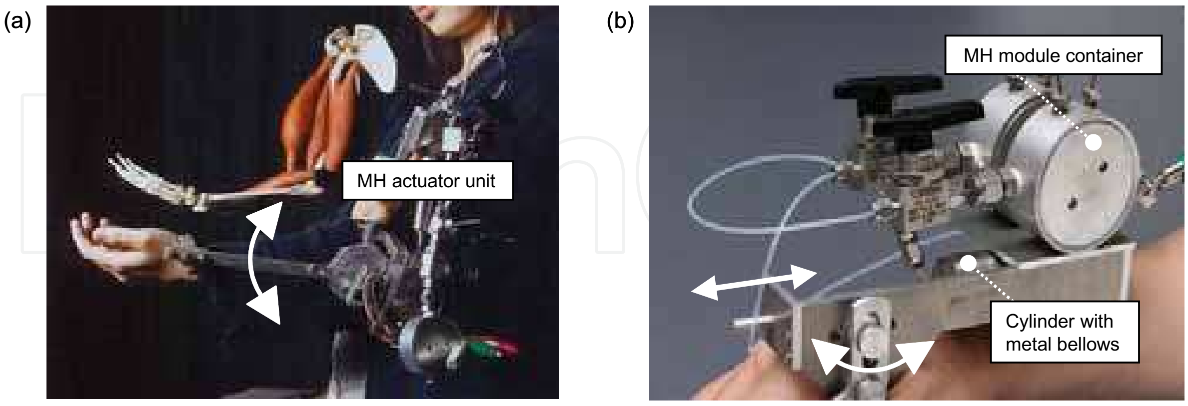

Fig. 14. Elbow CPM machine using an MH actuator unit (left) and the main components of its MH actuator unit (right).

As for the rest, our collaborative company has also developed a toilet seat lifter using an MH actuator (Wakisaka et al., 1997). This toilet seat lifter was installed in a house, which was called the Welfare Techno House in Japan (Tamura, 2006), for a case study of the well being of elderly people.

5.3 Sit-to-Stand Assist Cushion

The lifting systems of the wheelchair seat lift and the transfer hoist obviously cannot use the other assistive equipment without modification. Therefore, we have designed a portable cushion system for assisting in the sit-to-stand motion, which can easily attach to an existing wheelchair or bed (Sato et. al., 2007). The MH actuator in this cushion system was fitted with an air bag and a hydrogen-to-air pressure conversion system.

The appearance of the portable cushion system for assisting with sit-to-stand motion is shown in Fig. 13. To convert the hydrogen pressure generated by the MH module into an air pressure, a metal bellows, an air cylinder, and an accumulator were connected in series as illustrated in Fig. 13. The air cylinder and the accumulator were joined via a check valve. In other words, this system is a small and quiet air compressor using an MH actuator, what is termed an MH air compressor. The cushion part, which is applied as air bags made of laminate film sheet, comes from compressed air pressure exhausted from the accumulator to an elevating force as a stand-up support for a seated person. This cushion system contains a 12-g MH alloy. The output force is about 500 N, and the changing height of a seat is 90 mm. As the driving gas in the air bag is common air and not hydrogen, a hydrogen leakage safety concern is not an issue.

5.4 Continuous Passive Motion Machine

In the aging society, there are many needs for at-home instruments for motor rehabilitation in stroke or joint injured patients. The techniques of joint rehabilitation include manual therapy and range of motion (ROM) exercises using a continuous passive motion (CPM) machine. The therapeutic effects of these techniques were clinically clear in previous studies

(Salter et al., 1984). However, current CPM machines have some problems such as a lack of softness that inheres in human body, a bulky size for use, and noise emitted from the use of an electric motor. These problems disturb the ease and safety of use of the CPM machine at home. Hence, we have designed a compact MH actuator and prototyped a CPM device using it.

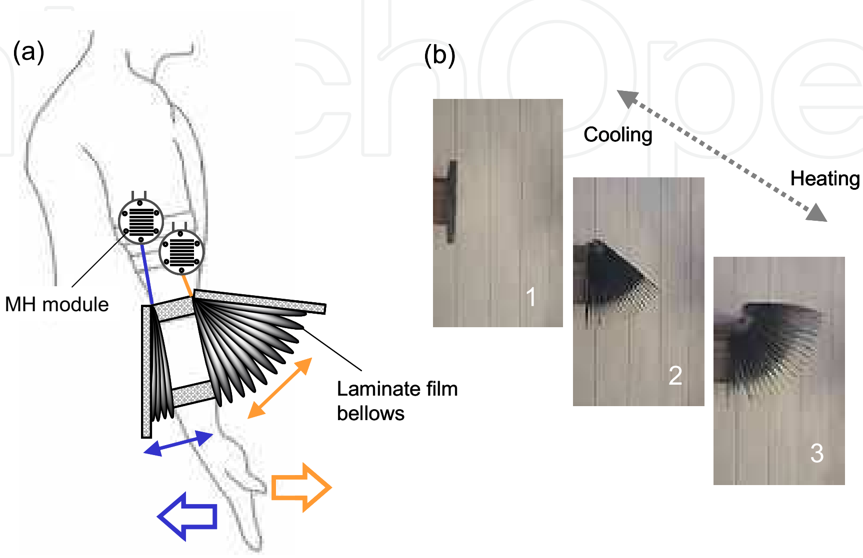

Fig. 15. Image of the elbow CPM machine using a pair of laminate film bellows and MH modules (left) and example of a motion pattern of the laminate film bellows added of an asymmetric elongation structure.

The prototyped CPM device for an elbow joint is shown in Fig. 14. The installed MH actuator contained a small metal bellows. The output torque around an elbow was about 7 Nm at maximum, which was selected based on the data obtained by the manual therapy motion of a physical therapist. The weight of this device was about 1.7 kg, and it is much lighter than that of a conventional CPM machine. The variable range of the mechanical compliance was 6.5 to 15 deg/Nm. Although this CPM machine has the potential to significantly improve joint disease, its weight and wearability are still not enough for clinical use.

In order to solve this problem, we designed a different type of CPM machine, which uses a laminate film bellows integrated into a soft MH actuator (Ino et al., 2008), as shown in Fig. 15. The antagonistic mechanism composed of two soft MH actuators allows for soft actuation of the elbow joints, and its stiffness can easily be controlled based on the sum of the inner pressure of both laminate film bellows (Sato et al., 1996).

Moreover, the range of the variable stiffness of human muscle at full activation was included in that of the MH actuator, as shown already in Fig. 10. Thus, the MH actuator using the laminate film bellows is suitable for a physical rehabilitation apparatus considering mechanical impedance matching.

By using the MH actuator, an extremely slow motion that is not available by a human hand be applied to a patient's joint, so it may allow some kind of effective exercise for early ROM rehabilitation after joint surgery, the cure of club-foot and other joint diseases.

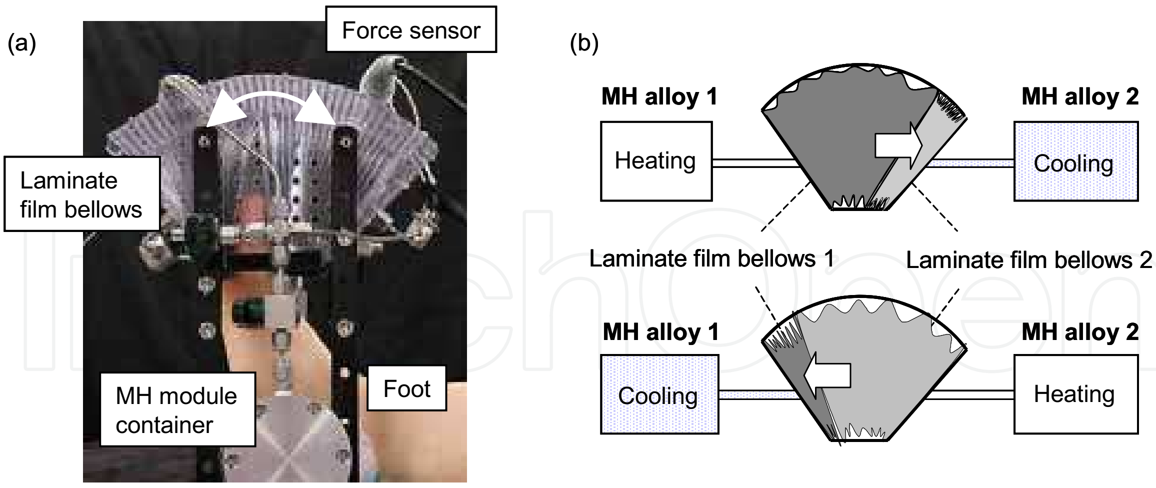

Fig. 16. Power assist system using the soft MH actuator units for toe exercises to prevent symptoms of disuse syndrome (left) and a schematic illustration of its antagonistic driving mechanism using a pair of the soft MH actuator units (right).

5.5 Power Assist Device

We have developed a bedside power assist system for toe exercises that can be configured from two of the soft MH actuators with a laminate film bellows, pressure sensors, a bipolar power supply, and a PID controller using a personal computer, as shown in Fig. 16 (a). The laminate film bellows of the soft MH actuator weighed 40 g.

A sketch of an antagonistic motion pattern of the soft MH actuators is shown in Fig. 16 (b). The extension and flexion motion of the toe joints are derived from a pair of soft bellows spreading out in a fan-like form in a plastic case. The motion of the toes in the power assist system was properly gentle and slow for joint rehabilitation. During the operation of the system, the subject's toes constantly fitted in the space between the two soft bellows.

Thus, various toe joint exercises could be easily actualized by a simple pressure control of the soft MH actuator system. In addition, we have measured the cutaneous blood flow before and during exercise to examine the preventive effect on bedsore formation by a passive motion exercise (Hosono et al., 2008). These results show a significant blood flow increase at the frequent sites of decubitus ulcers. The passive motion at toe joints using such a soft MH actuator will be useful for the prevention of disuse syndromes (Bortz, 1984).

6. Conclusion

In this chapter, we explained a novel soft actuator using an MH alloy and its applications in assistive technology and rehabilitation engineering. The MH actuator using metal hydride materials has many good human-friendly properties regarding the force-to-weight ratio, mechanical impedance, and noise-free motion, which are different from typical industrial actuators. From these unique properties and their similarity to muscle actuation styles of expansion and contraction, we think that the MH actuator is one of the most suitable force devices for applications in human motion assist systems and rehabilitation exercise systems. Additionally, by producing a much larger or smaller MH actuator by taking advantage of the uniqueness of its driving mechanism and the simplicity of its configuration, its various applications may extend in other industrial areas such as a micro-actuator for a functional endoscope, a manipulator for a submarine robot, a home elevator system, and so on.

The energy efficiency and the speed of the contraction mode of the MH actuator are the main issues to be improved when considering the increasing use of this actuator. The cause of these issues is derived from the use of a Peltier module for the temperature control of the MH alloy. Thus, technological developments on the Peltier module with supreme heat conversion efficiency or a method of high-speed heat flow control are demanded for a performance gain of the MH actuator.

In an aging society with a declining birth rate, the demand for motion assist systems and home care robots for supporting well-being in daily life will be increased from a lack of labor force supply, especially in Japan which has been faced with a super-aged society. It is important to make sure a biomedical approach is taken to developing the soft actuator considering sufficiently human physical and psychological characteristics, a thinking pattern that is different from that of a conventional industrial engineering approach. At present, a human-friendly soft actuator is strongly demanded to progress quality-of-life technologies. For a further study, we will focus on putting the soft MH actuator into practical use to serve the elderly and people with disabilities in daily life at the earliest possible date.

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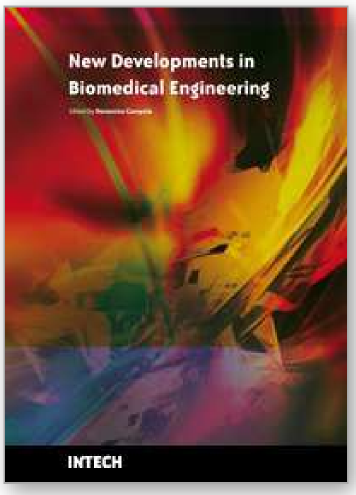

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