# Designing a Metal Hydride Actuator with Human-Compatible Softness and High Power-to-Weight Ratio for Future Quality-of-Life Technologies

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**Abstract.** Japan faces a rapidly growing elderly population that is unprecedented in the world. As a result, there are emerging needs for quality-of-life technologies, such as rehabilitation equipment, long-term care, and assistive devices. In particular, elderly people who are bedridden due to physical illnesses, such as cerebral stroke or bone fractures caused by a fall, may suffer awkward disuse syndromes (e.g., pressure ulcers, joint contracture, cardiac hypofunction, and mental depression). It is difficult for them to actively participate in rehabilitation exercises by themselves. Thus, to manage these disuse syndromes, we have developed a light and soft actuator device with metal hydride materials. This actuator device has a high power-to-weight ratio, adequate softness for human body support, noiseless motion, and a clean hydrogen energy system. The three apparatuses in which the metal hydride actuator is applied are a joint rehabilitation device for the hand, a seat lifter for a wheelchair or toilet, and a toe exercise apparatus for bedsore prevention.

**Keywords:** Super-aging society, long-term care, rehabilitation, soft actuator, metal hydride material, power assistance, quality-of-life technology.

## 1 Introduction

It is well known that older segments of the population within developed countries are expanding faster than younger segments. Longer life expectancies coupled with a

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general decline in the birthrate are leading to a dramatic shift in the proportion of people aged 65 years or over in the total population. By 2030, one in every three persons in Japan will be 65 years or over, and one in five persons will be 75 years or over. Reflecting improvements in health and the living environment after World War II, Japanese life expectancy at birth has become the highest in the world: 80 for males and 86 for females as of 2009 [1].

Demographic researchers, gerontologists, and economists in Japan have been attempting for several decades to alert the people of Japan to the fact that, collectively speaking, they are rapidly growing older. Population aging affects national and local economies in terms of healthcare services, pensions, and the long-term care system. The shortage of caregivers and nurses has led to the need to develop assistive devices and rehabilitation apparatuses to sustain several activities of daily life (ADL).

In particular, older patients who are required to lie down for long periods due to illness or injury may suffer disuse syndromes, including pressure ulcers, joint contracture, muscular atrophy, cardiac hypofunction, and mental depression. It is often difficult for these vulnerable older patients to actively exercise for physical rehabilitation and improved ADL. To help manage these disuse syndromes, rehabilitation equipment and assistive devices, such as compact apparatuses for continuous exercise of joints, power assistance devices to enable standing or lifting, and bedsore-prevention systems, are strongly needed at the bedside. These equipment and technologies demand soft and compact actuators to replicate the effort of human muscles.

Currently, there are no commercially available actuators that contain human-compatible softness for safety, noiselessness for comfort, and a high power-to-weight ratio similar to human muscles. These technical requirements present a large challenge to the development of rehabilitation engineering and assistive technologies. To solve these challenges, many types of artificial muscle-like actuators, such as pneumatic rubber actuators [2], shape memory alloy (SMA) actuators [3], and polymer actuators [4], have been actively studied by material scientists and biomedical engineers. Unfortunately, satisfactory results in terms of actuators that can actually contribute to rehabilitation, self-independent living, or long-term care have not yet been achieved.

We have been the first to develop a novel, soft and compact actuator using metal hydride materials [5]. A metal hydride (MH) actuator can produce a soft and powerful force even though it is small and light because the metal hydride materials can store hydrogen gas volumes in amounts that are over 1,000 times larger than its own volume by controlling its temperature. Moreover, the MH actuator has adequate softness and a noiseless motion for applications in rehabilitation and assistive devices. An additional potential merit is that hydrogen is a clean-energy carrier candidate, which contributes to a sustainable energy society [10].

The purpose of this paper is threefold: first, to overview the properties of metal hydride materials as soft and compact actuators applied in rehabilitation and long-term care apparatuses; second, to describe the fundamental structure of the MH actuator and its performance using experiments; and third, to show several applications of the MH actuators in rehabilitation and assistive technologies, including a continuous passive motion (CPM) device for joint therapy, a seat-lift apparatus for people with restricted mobility, and a compact foot-exercise apparatus for the prevention of bedsores.

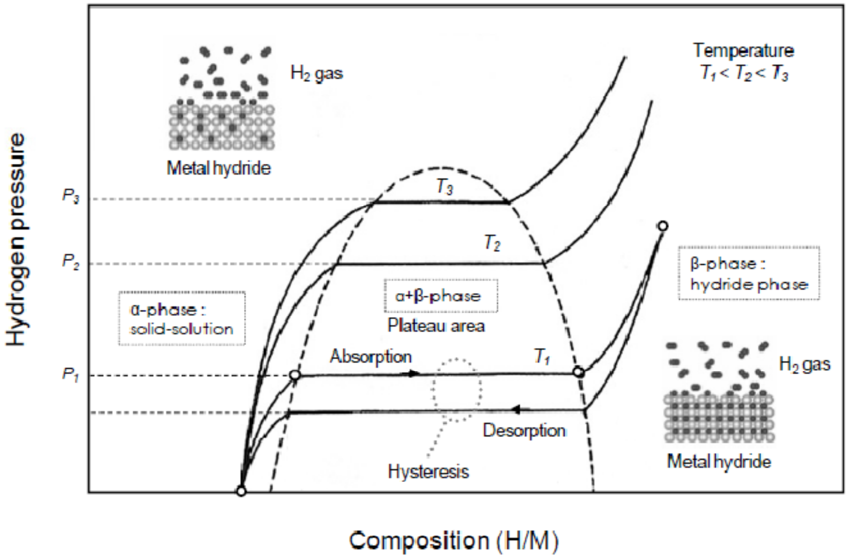


**Fig. 1.** Pressure-composition-temperature (PCT) diagram of a metal hydride material under hydrogenation.

## 2 Metal Hydride Actuator

### 2.1 Metal Hydride Materials

Metal hydride materials (i.e., hydrogen-storing alloys) have the ability to store a volume of hydrogen gas that is 1,000 times or more greater than the volume of the alloy itself. The compressibility of hydrogen in the MH material is higher than that of a high-pressure gas cylinder or liquid hydrogen storage.

The general hydrogen-absorbing and -desorbing properties of the MH material are described by the following reaction formula:

$$\mathrm{M} + \frac{x}{2}\mathrm{H}_2 \rightleftarrows \mathrm{MH}_x + Q \tag{1}$$

where M is the metal, $H_2$ is hydrogen gas, $MH_x$ is the metal hydride, and $Q$ is the heat of reaction. Thus, $Q > 0$ J/mol for $H_2$.

Moreover, the hydrogen equilibrium pressure ($P$) is related to the changes in enthalpy ($\Delta H$) and entropy ($\Delta S$) 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 logarithmic equilibrium pressure is proportional to an inverse function of the temperature. As shown in Fig. 1 (i.e., the PCT diagram), if

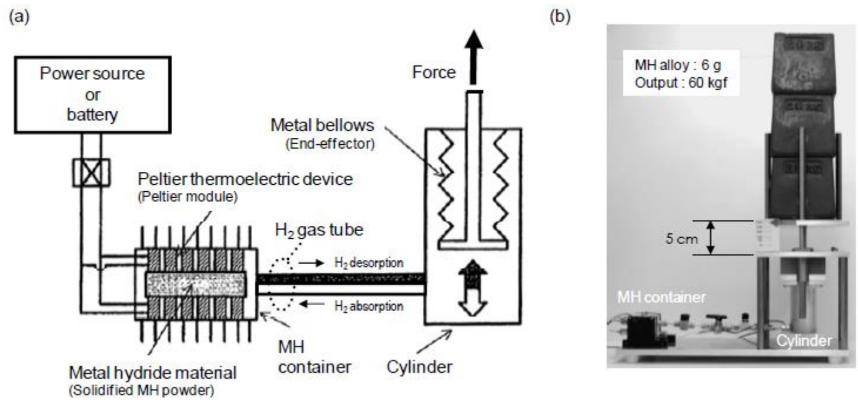


**Fig. 2.** (a) Basic schematic structure of an MH actuator system. (b) The prototype MH actuator with a metal bellows cylinder and a Peltier module in the MH container.

this reaction proceeds at a constant temperature, then it advances up to an equilibrium pressure, which is called the plateau pressure. As demonstrated in the PCT diagram, the plateau pressure can be regulated by changing the MH material temperature.

Fortunately, the MH material is not flammable, so it is safe as a solid hydrogen storage for a fuel battery in electric vehicles and mobile applications [6].

## 2.2 Power-to-Weight Ratio

MH materials can not only store a large amount of hydrogen gas efficiently but can also release the gas through temperature control. If this reversible chemical reaction is carried out in a hermetically closed container system, the heat energy applied to the MH material is converted into mechanical energy via an equilibrium pressure change inside the MH container. The MH actuator performs by using the hydrogen pressure generated by the MH material due to added heat energy, which can be controlled by, for example, an electrically heated wire, a Peltier module, or a solar thermal collector.

An MH actuator is composed of a solidified MH powder, a Peltier module, a temperature sensor, an enclosure for these elements, and an end effecter to change the hydrogen gas pressure into a driving force, as shown in Fig. 2(a).

For example, the MH actuator system shown in Fig. 2(b) includes 6 g of metal hydride and a 36-mm-diameter metal bellows. This MH actuator can lift a 60-kg weight without any noise; this represents a high power-to-weight ratio of approximately 10,000. The power-to-weight ratio of the MH actuator is much higher than that of familiar industrial actuators, such as electric motors and pneumatic actuators. Because its mechanism involves direct heat-to-mechanical energy conversion, the MH actuator does not make any noise or vibration. In addition, the reversible hydrogen absorption and desorption in the metal hydride also produces a soft cushion effect, which

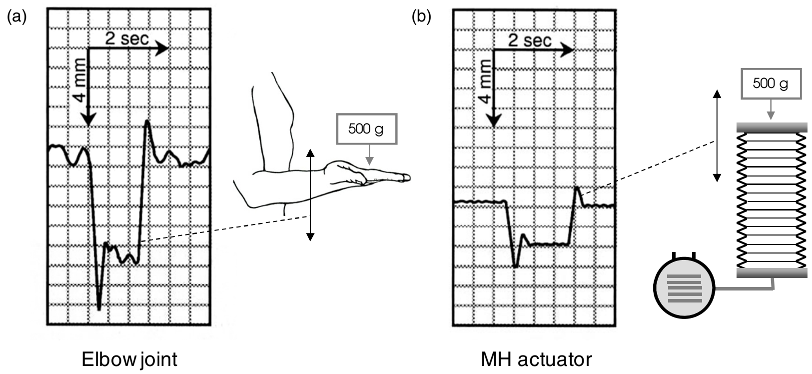


**Fig. 3.** Dynamic response of (a) the elbow joint and (b) the metal bellows of the MH actuator under step loading of 500 g.

improves the safety for the human and prevents mechanical overload of the device. Therefore, MH actuators are novel human-sized actuators that can be applied to rehabilitation systems and assistive devices requiring softness and quietness.

### 2.3 Softness Analogous to That of the Human Elbow

The human musculoskeletal system can make both gentle and powerful forces during various nursing and therapeutic exercises, which are needed for people with physical disabilities or vulnerable older people. However, it is difficult for state-of-the-art robots and machinery that use conventional actuators and mechanical parts to perform like humans.

To measure the elasticity (i.e., softness) of the MH actuator, the dynamic elasticity of both an MH actuator with a single metal bellows and the elbow joint of a healthy young subject were compared through the step response of dropping a 500-g weight. The displacement patterns of the step response were similar to one another as shown in Fig. 3.

The elasticity of the MH actuator with a metal bellows was also measured by a universal tester. The relationship between the stiffness and the inner pressure of the metal bellows for the initial inner parameters of the MH actuator is shown in Fig. 4. The stiffness increased with increasing pressure inside the metal bellows. Moreover, the range of stiffness of the MH actuator system when placed as a pair of antagonistic metal bellows, which replicates a musculoskeletal system, is compatible with that of the human elbow joint during voluntary movement [7]. Thus, this elastic feature of the MH actuator allows a technical solution for physical therapy and long-term care applications.

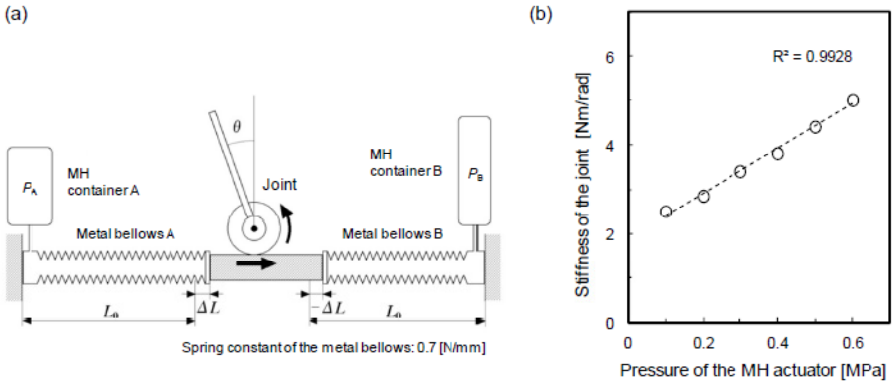


**Fig. 4.** (a) Schematic of the experimental setup used for the joint stiffness measurement of a double-acting MH actuator system. (b) Joint stiffness profiles of the MH actuator system at each given pressures: $P_A$=$P_B$.

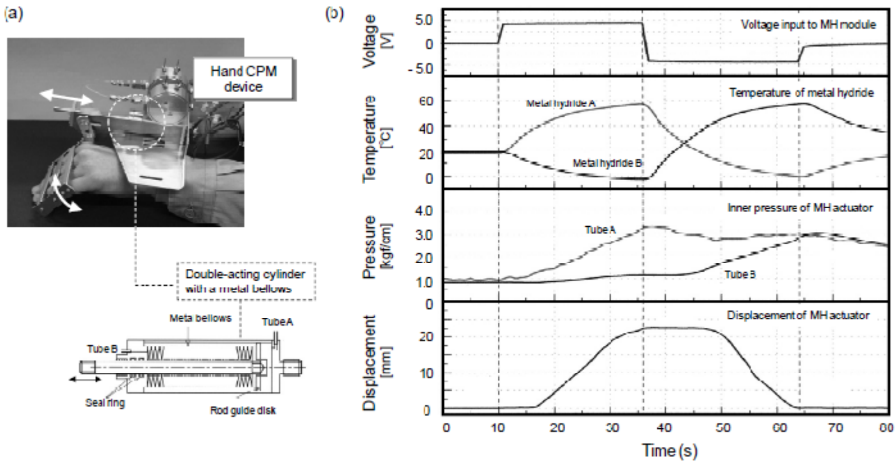


**Fig. 5.** (a) Photograph of a prototype hand CPM device that targets the finger joints. (b) Dynamic behavior of the compact double-acting MH actuator installed in the hand CPM device.

## 3 Joint Rehabilitation Device

Rehabilitation methods for joint therapy include manual therapy by a human (e.g., a physician, physical therapist, or occupational therapist) and range of motion (ROM) exercises using a CPM device. The therapeutic effects of CPM, which include the prevention of joint contracture, muscular atrophy, and ROM loss after joint injury,

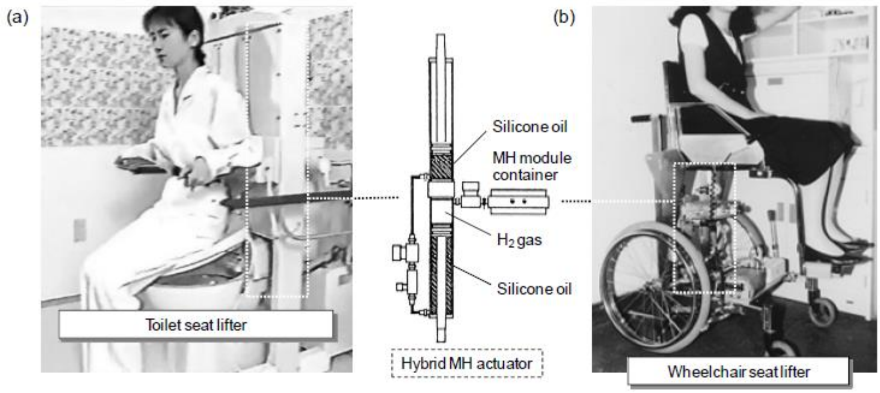


**Fig. 6.** Photograph of a seat lifter using the hybrid MH actuator having a hydrogen-hydraulic converter for (a) a toilet assembly and (b) a wheelchair.

have been shown in previous clinical studies [8]. Current CPM devices, however, have problems relating to stiffness, noise, and size. Thus, we designed a compact CPM device using MH actuators.

The CPM device for hand rehabilitation is shown in Fig. 5(a). This CPM device was installed with a compact MH actuator that includes a small push-pull metal bellows covered with a metal sleeve and a pair of MH containers with 3 g of MH powder and a Peltier module. The output force and stroke of the MH actuator were 100 N and 20 mm, respectively. The weight of the MH actuator was 250 g. The hand CPM device using the MH actuator was much lighter than conventional CPM devices, which are built out of an electric motor and many mechanical parts.

To evaluate the behavior of this hand CPM device, the MH actuator was driven by a voltage input in the range from – 4 V to 4 V, and the responses were measured. Fig. 5(b) shows an example displacement pattern of the rod of the MH actuator. It was observed that the push-pull motion of the compact MH actuator was noiseless and smooth within the allowable bounds for a delicate ROM exercise for finger joint therapy.

## 4 Seat Lifting Apparatus

Assistive devices to support standing or lifting up of the human body must secure a smooth and long stroke motion for users (i.e., people with lower limb disability, vulnerable elderly people, and caregivers). For this purpose, a hybrid MH actuator that uses a long tandem piston cylinder with a hydraulic converter was developed. By applying this hybrid driving mechanism with a hydrogen-hydraulic converter, the stroke displacement is doubled compared with a common MH actuator driven by only hydrogen gas from metal hydrides.

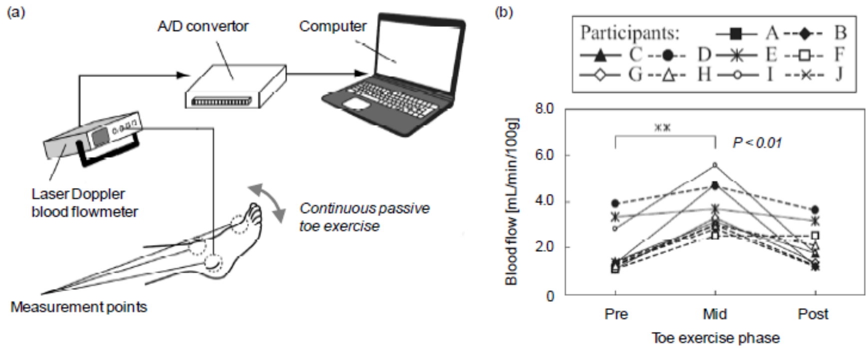


**Fig. 7.** (a) Experimental setup for the continuous passive exercise of toe joints and meaurement site locations for subcutaneous blood flow in the foot. (b) Subcutaneous blood flow rate of pre-, mid-, and post-exercise at the base of the first toe.

The toilet seat lifter system featuring the hybrid MH actuator is shown in Fig. 6(a). The toilet-seat lifting function has a similar hybrid MH actuator system to that described above. This toilet-seat lifting system had 150 g of MH powder and could lift a 100-kg weight to a 35-cm height. The lifting speed was 10 mm/s. To heat and cool the compacted MH powder, we adopted an electric heating wire and a water jacket with cold in-house tap water, respectively, as a simple heat exchange system that also saves energy.

For wheelchair applications, a hybrid MH actuator with 40 g of MH powder can lift an 80-kg weight to a 40-cm height as shown in Fig. 6(b). The lift speed was 20 mm/s, and the total weight of the lifting unit including the MH actuator with the tandem piston cylinder was 5 kg.

## 5 Bedsore Prevention Apparatus

Pressure ulcers (i.e., bedsores) can arise when a prolonged mechanical load is applied to soft biological tissues. These sores interfere with quality of life, daily living activities, and rehabilitation and, in some cases, may prove life-threatening. To prevent pressure ulcers in the elderly and people with motor disabilities, it is important to maintain subcutaneous blood flow, to relieve the pressure on soft tissues, and to obtain proper nutrition [9].

Initially, we performed measurements of the subcutaneous blood flow at common sites where pressure ulcers arise during passive toe exercises. Subcutaneous blood flow was measured at the base of the first toe and at the lateral malleolus using a laser blood-flow meter. The blood flow rate data were acquired for 1 minute before exercise (pre-exercise), 2 minutes during exercise (mid-exercise), and 1 minute after exercise (post-exercise) in each trial. Ten healthy subjects aged from 20 to 80 years participated in this experiment after giving informed consent.

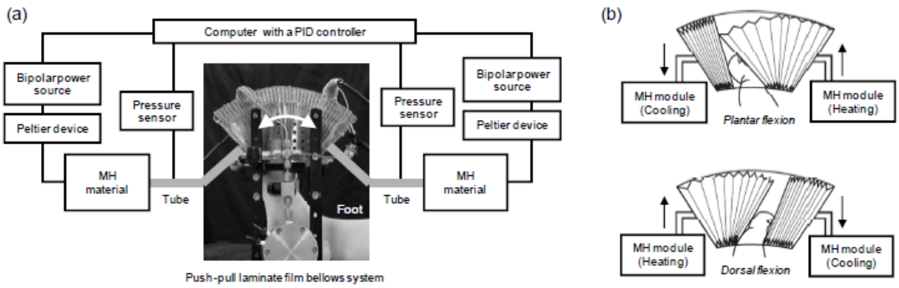


**Fig. 8.** (a) Block diagram of the prototype bedsore prevention apparatus. (b) Schematic of a motion pattern for controlling a pair of soft MH actuators with laminate film bellows.

From the experimental results, the blood flow rate at the base of the first toe during the exercise was significantly higher ($P < 0.01$, Wilcoxon test) than before the exercise as shown in Fig. 7. The blood flow rate at the lateral malleolus exhibited the same trend ($P < 0.02$, Wilcoxon test). The results suggest that the continuous passive exercise of toe joints can prevent bedsores and soft tissue contracture induced by ischemia.

We then developed a prototype of the bedsore prevention apparatus based on mild toe exercises using a fan-shaped soft MH actuator that has laminate film bellows [5] and can easily fit various foot forms as shown in Fig. 8. The extension and flexion motion of the toe joints was derived from a pair of laminate film bellows that spread out in sectors of the bedsore prevention apparatus. The motion of the subject's toes by using this apparatus was enough to increase subcutaneous blood circulation. During the operation of the apparatus, many subjects' toes (i.e., variable sized and shaped toes) could always fit into the space between the antagonistic laminate film bellows of a pair of the MH actuators.

The motion patterns for the joint exercises were produced by the regulation of the pressure combination of both MH actuators. Linear control over the flexion and the extension angle of the toes was obtained by altering the difference between the inner pressures of each laminate film bellows through the pair of MH actuators. The stiffness of the movable part inserted between both laminate film bellows was determined by evaluating the sum of the inner pressures of both bellows. Thus, both the angle and the stiffness of toe motion could be controlled independently.

## 6 Conclusion

In this paper, we described a soft and noiseless actuator using MH materials and its applications in assistive technology and rehabilitation engineering. The MH actuator has several unique features, including a high force-to-weight ratio, low mechanical impedance, noiseless motion, and a muscle-like actuation mechanism based on expansion and contraction that differs from conventional industrial actuators. Based on these distinctive features, we believe that MH actuators are suitable force devices for applications in human motion assistance, long-term care, and rehabilitation exercise.

Initial applications of the MH actuator were developed including a CPM device, a seat lifter for a wheelchair or toilet, and a bedsore prevention apparatus. Further works with an interdisciplinary approach among rehabilitation engineering, material science, medicine, and robotics should help these novel MH actuators become applicable to devices in which human-friendly motion is desirable for future quality-of-life technologies.

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