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(54) **PORTABLE ENERGY STORAGE DEVICES AND METHODS**

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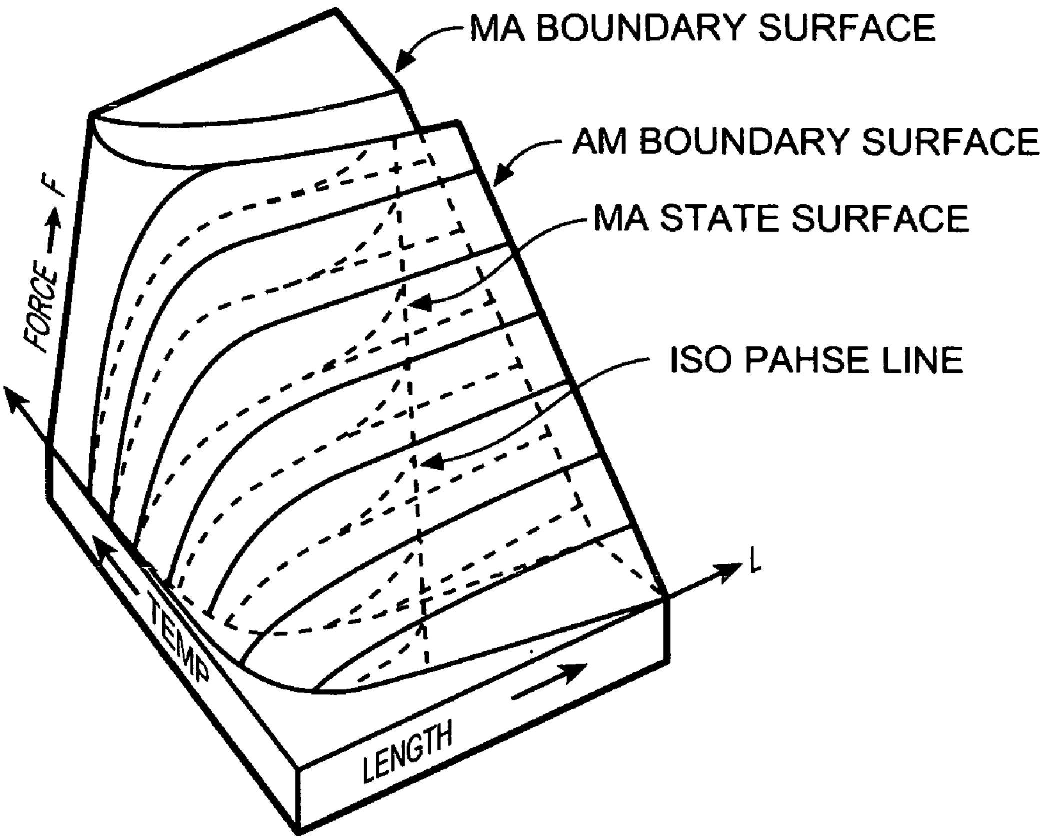
(52) **U.S. Cl.** **148/404**

(57) **ABSTRACT**

Devices and methods which store and selectively release relatively substantial amounts of energy for enabling individuals to undertake superior performance in locomotion and other physical activities. The different embodiments include a hyperelastic SMA element which stores and releases energy in a differential pulley set, in a hinged knee, and in a pogo stick.



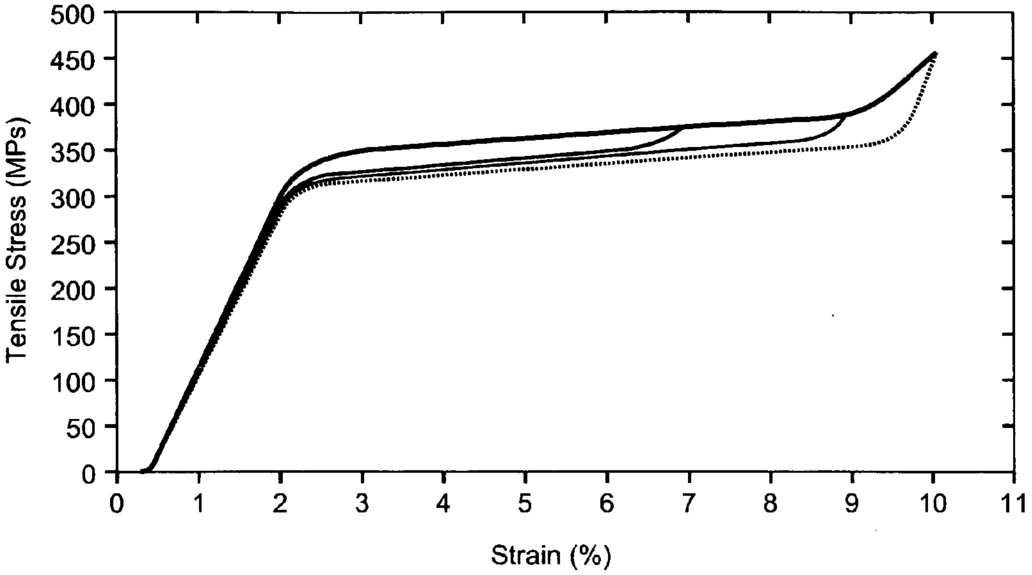

Tensile Stress (MPs)
500
450
400
350
300
250
200
150
100
50
0
0
1
2
3
4
5
6
7
8
9
10
11
Strain (%)

FIG. 1

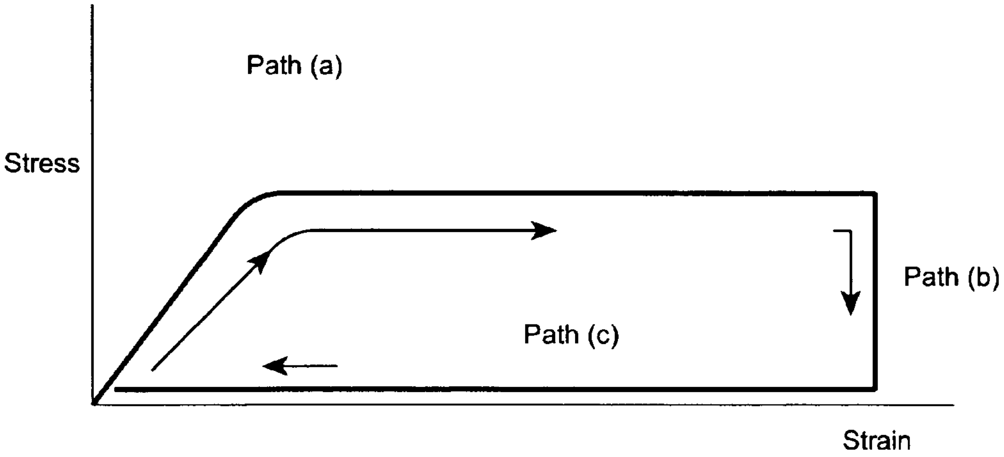

Path (a)
Stress
Path (b)
Path (c)
Strain

FIG. 2

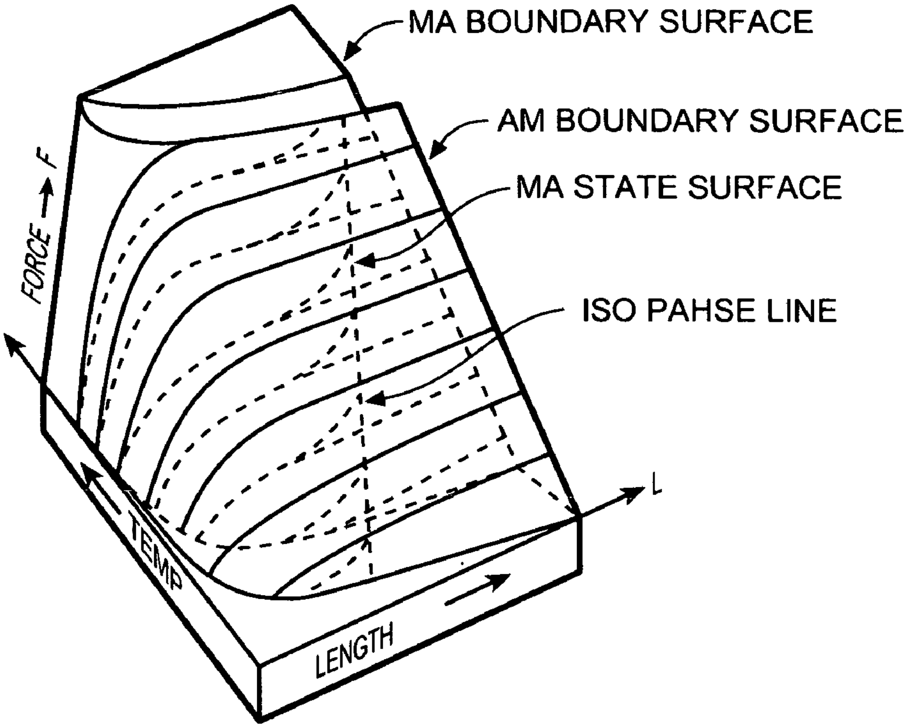

MA BOUNDARY SURFACE
AM BOUNDARY SURFACE
MA STATE SURFACE
ISO PAHSE LINE
FORCE → F
L
TEMP
LENGTH

FIG. 3

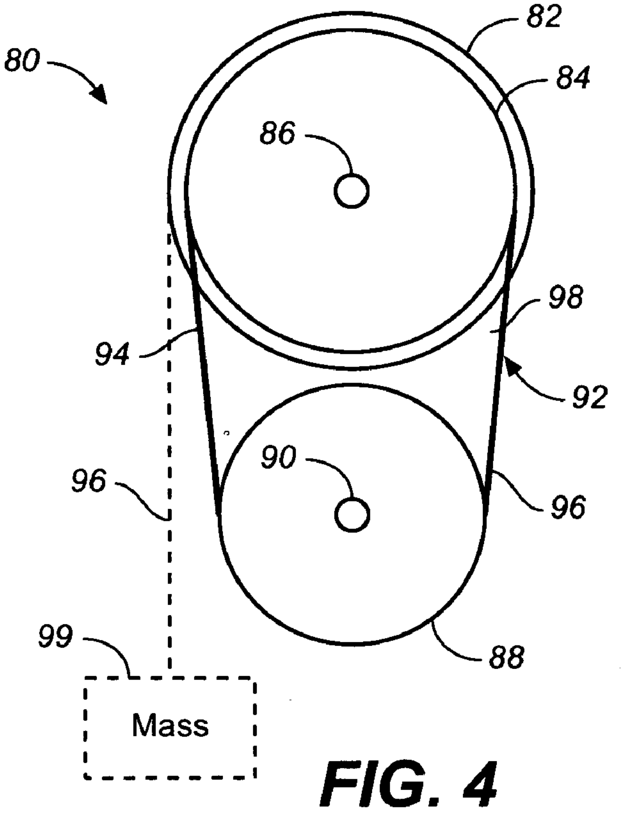

80
82
84
86
98
94
92
90
96
96
88
99
Mass

FIG. 4

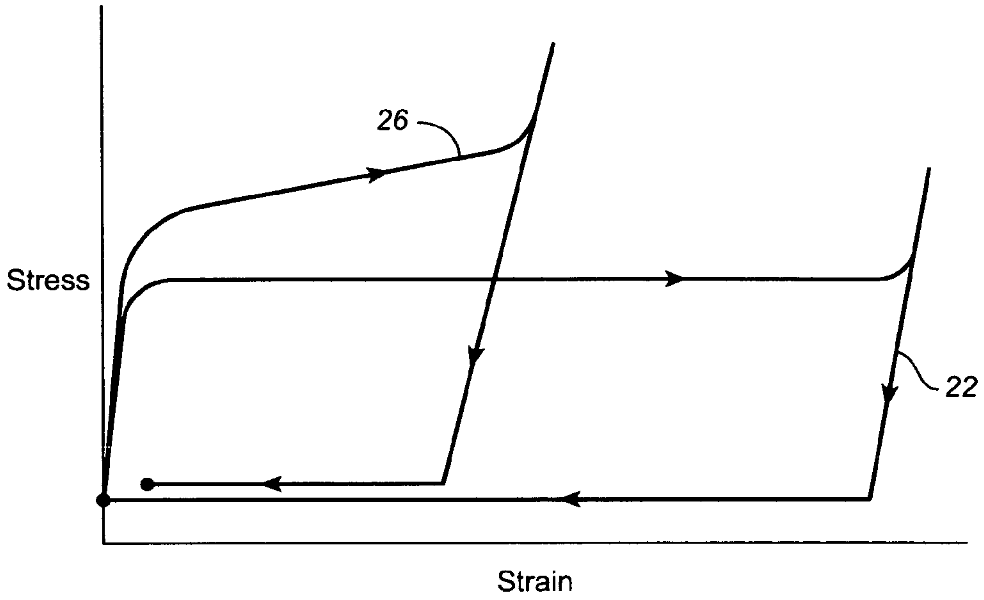


FIG. 5

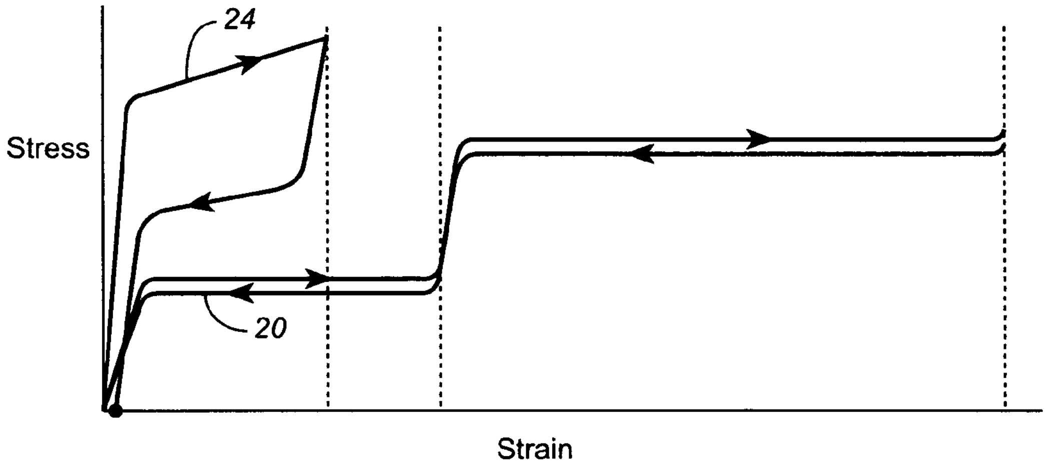


FIG. 6

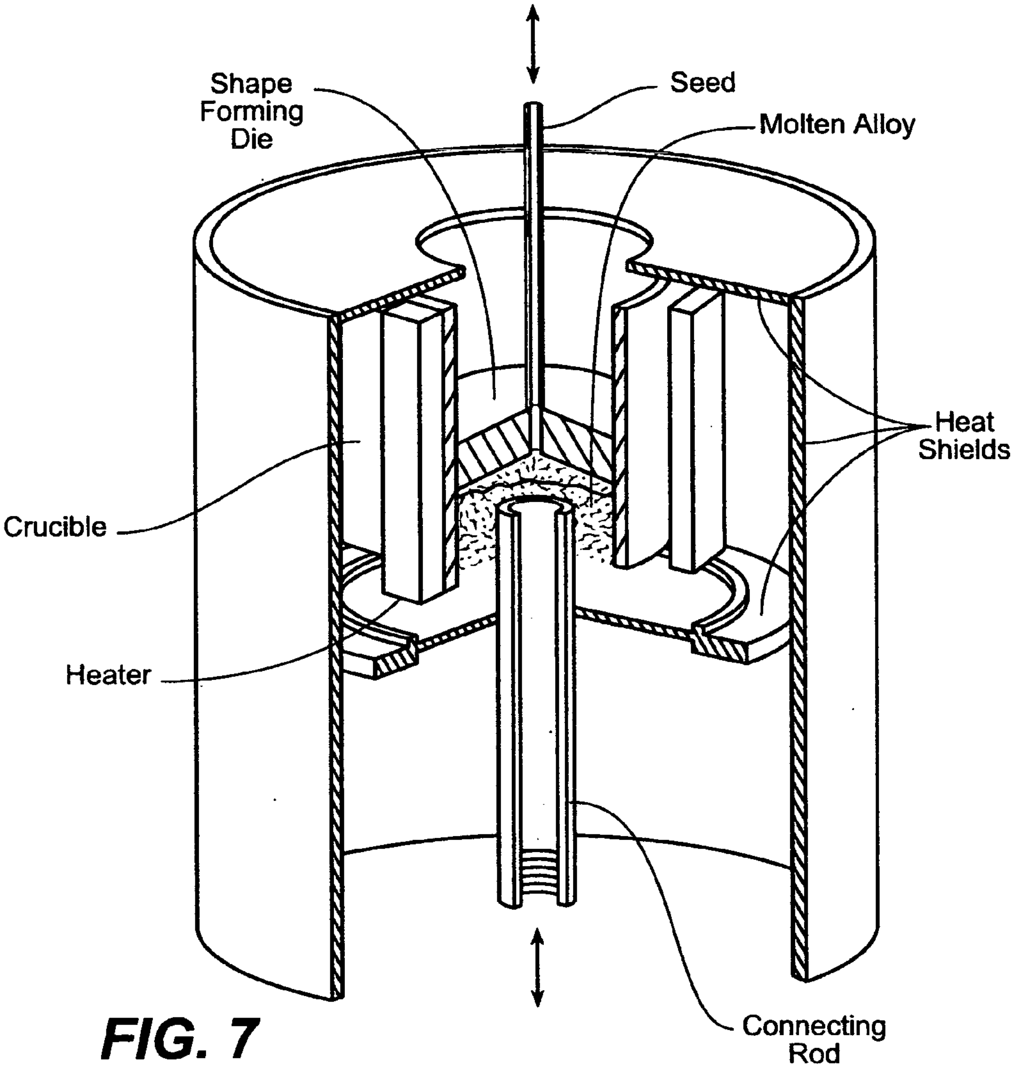

Shape
Forming
Die
Seed
Molten Alloy
Heat
Shields
Crucible
Heater
Connecting
Rod

FIG. 7

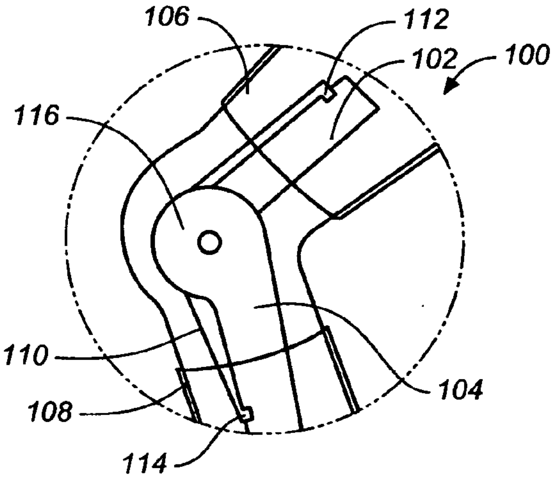

106
112
102
100
116
110
104
108
114

FIG. 8

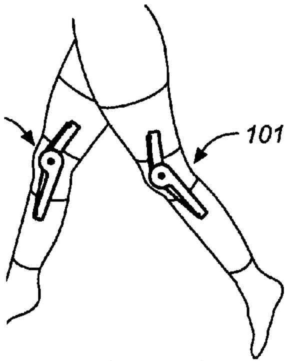


FIG. 9A

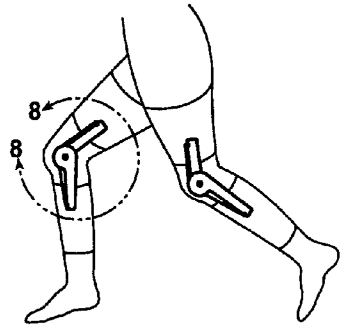


FIG. 9B

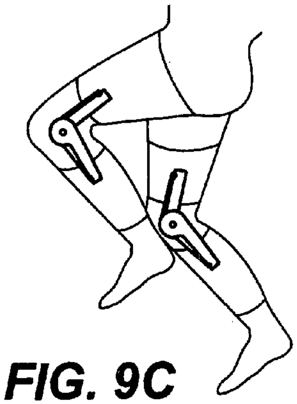


FIG. 9C

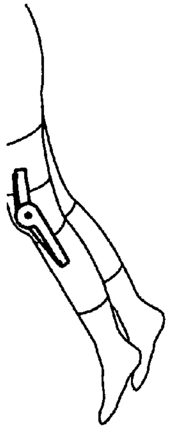


FIG. 9D

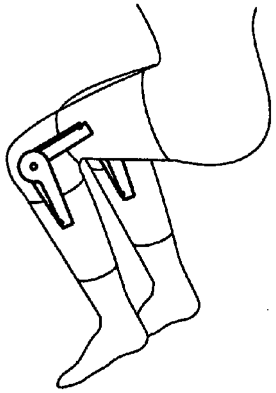


FIG. 9E

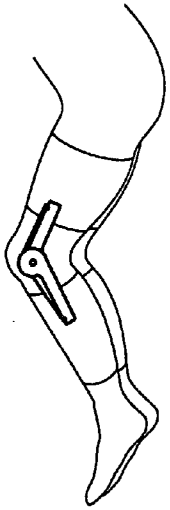


FIG. 9F

Table I

Density 7.1 grams/cm^3
Cp = 0.5 joule/gram/deg.C
Thermal Conductivity 30 to 43 watt/m*deg.C*
Young's modulus 80-85 Gpa
Yield strength Martensite: 130 Mpa, Austenite: 400 Mpa
Ultimate tensile strength 500-800 Mpa
Mechanical energy greater than 4 joules/gram
Rise of Stress Plateau with Temperature = 2 MPa/deg.C
Latent heat 8.3 joules per gram (Martynov)
Ambient temperature = 26 deg.C
Material is superelastic: ~50 degrees C above A_f
Stress is greater than 300 MPa
Strain is greater than 9 %
Permissible acceleration is 18 Gs for less than 100 msec
Energy is conserved.

FIG. 10

Table II

Mass of Payload, kg	80		160	Increased
Height, meters	4		2	Decreased
Energy, joules = Newton-meters	3200		3200	
Plateau Stress, Mpa	300		300	mega-newt/m^2
CuAlNi Density, Kgm/m^3	7100		7100	
Fractional elongation delta-L/L	0.10		0.10	
Energy density, j/gm	4.23		4.23	
Mass CuAlNi required, kg	0.76		0.76	
Number of Wires	1		1	***
Mass of each wire, kg	0.76		0.76	
Radius of Larger pulley, meters	0.43		0.43	
Radius of Smaller pulley, meters	0.31		0.31	
Radius of Idler pulley, meters	0.1		0.1	
Radius of Cable Drum, meters	1.2841	LARGE!	0.642	
Distance between Pulley Shaft Centers, m	0.55	OK	0.55	
L = Length of CuAlNi wire, meters	3.74		3.74	
Change in wire length, meters	0.37		0.37	
Total x-section, meters^2 [square x-section]	0.00003		0.00003	Mass/(l*rho)
Diameter of each wire, m;[Square x-sec]	0.0053		0.0053	
Tensile Force = Stress* Area, newtons	8562		8562	
Torque, newton-meters	1027		1027	
Change in wire length, meters	0.374		0.374	
Angle through which pulleys turn, radians	3.11	OK	3.11	1/2 turn.
Potential Work Available, joules [Torque* Angle]	3200		3200	Torque*angle
Height that mass is lifted, Meters	4.000		2.000	
Actual work done, joules [Mass* Height]	3200		3199	

FIG. 11

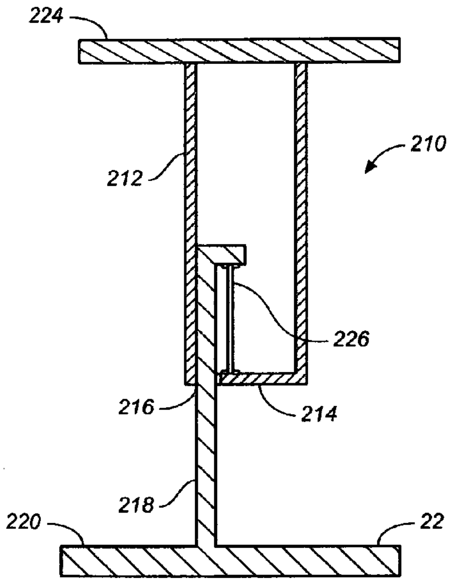


FIG. 12

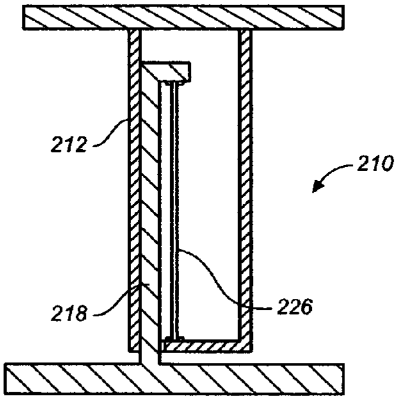


FIG. 13

PORTABLE ENERGY STORAGE DEVICES AND METHODS

CROSS-REFERENCE TO PRIOR APPLICATIONS

[0001] This application claims the benefit under 35 USC §119(e) of U.S. provisional patent applications Ser. No. 60/615,846 filed Oct. 4, 2004; 60/637,741 filed Nov. 22, 2004; and 60/658,862 filed Mar. 7, 2005.

BACKGROUND OF THE INVENTION

[0002] 1. Field of the Invention

[0003] The invention relates to the storage and release of mechanical energy by portable devices.

[0004] 2. Description of the Related Art

[0005] A warfighter on foot must carry equipment and is often required to move fast and over terrain that requires increased physical effort. It is recognized that increasing the mobility of the footsoldier makes him or her more effective in combat and other situations.

[0006] Exoskeletons have been demonstrated that provide super strength for individuals. Driven by electrical stepper motors, these require a source of energy, usually batteries which are too heavy to be practical for operational use.

[0007] The idea of storing mechanical energy to enhance the physical capabilities is incorporated in an invention by Nicholas Zagn of Saint Petersburg Russia in 1890. His apparatus used conventional springs that are limited to less than one percent strain, and have varying force according to Hooke's law. This does not provide an optimum energy source for locomotion.

[0008] The prior art has not provided a compact, light-weight and portable device for storing sufficient amounts of potential energy which can be quickly released into kinetic energy for enhancing human locomotion and other physical activities.

[0009] The need has therefore been recognized for compact, light-weight and portable devices that obviate the foregoing and other limitations and disadvantages of prior art devices of the type described. Despite the various devices of the type in the prior art, there has heretofore not been provided a suitable and attractive solution to these problems.

OBJECTS AND SUMMARY OF THE INVENTION

[0010] A general object of this invention is to provide devices and methods that store substantial amounts of potential energy which can be quickly released into kinetic energy sufficient for enhancing human locomotion and other physical activities.

[0011] Another object is to provide a portable 'passive' device which can store sufficient energy to lift individuals to a specified height, or alternatively to absorb the equivalent potential energy of descent from such a height.

[0012] The invention in summary provides devices and methods which store and selectively release relatively substantial amounts of energy for enabling individuals to undertake superior performance in locomotion and other physical activities.

BRIEF DESCRIPTION OF THE DRAWINGS

[0013] **FIG. 1** is a chart showing the stress-strain isotherm of a hyperelastic SMA for use in the invention.

[0014] **FIG. 2** is a chart showing the stress-strain cycle for a free-falling mass that is stopped by a hyperelastic spring in accordance with the invention.

[0015] **FIG. 3** is a chart showing the stress, strain and temperature variables of the theoretical paths for TiNi SMA.

[0016] **FIG. 4** is a schematic diagram showing a pulley arrangement using hyperelastic SMA in accordance with one embodiment of the invention.

[0017] **FIG. 5** is a chart comparing the stress-strain cycles of polycrystalline TiNi SMA with single crystal CuAlNi SMA in the martensite crystalline phase.

[0018] **FIG. 6** is a chart comparing the stress-strain cycles of polycrystalline TiNi SMA with single crystal CuAlNi SMA in the austenite crystalline phase.

[0019] **FIG. 7** is a partially cut-away perspective view of a crucible structure with a hot zone for growing single crystal SMA of round cross section for use in the invention.

[0020] **FIG. 8** is a side elevation view of a knee hinge device having hyperelastic SMA elements for human locomotion.

[0021] **FIGS. 9A, 9B**, 9C, 9D, 9E and 9F comprises side elevation views shown in sequential positions during vaulting of a human wearing on each knee the hinge devices of **FIG. 8**.

[0022] **FIG. 10** is a table listing the physical data for the hyperelastic SMA material in one preferred embodiment of the invention.

[0023] **FIG. 11** is a table listing the technical parameters in one preferred embodiment of the invention.

[0024] **FIG. 12** is a vertical section view of a pogo stick device in accordance with another embodiment showing the device in one operating mode.

[0025] **FIG. 13** is a vertical section view showing the device of **FIG. 12** in another operating mode.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

General Description

[0026] The invention provides devices and methods which enable an individual, such as a warfighter, to carry heavier loads and run faster without increasing demands on physical stamina; and to enable a person of ordinary ability to leap high enough to clear a high obstacle and thus to escape from a dangerous situation. When combined with suitable exoskeleton components, the devices and methods will enable a person to jump from a building or make a rapid descent by parachute without suffering injury due to sudden deceleration. It is particularly desirable that the devices not require electrical power, i.e. they are a 'passive' system that uses and amplifies human effort. The individual is enabled to function on the ground with the equipment in place. The devices are neither too heavy or bulky nor too restrictive or awkward. Otherwise it would have negative impact on the individual's mobility and effectiveness.

[0027] The invention provides an individual/warfighter with extraordinary abilities to run, carry heavy loads, and leap onto and from structures. The devices of the different embodiments are characterized in being compact while enabling the release of a sufficient quantity of mechanical energy to boost a human to heights not achievable by human muscle alone. Acceleration is constant during boost, and limited to tolerable levels. One embodiment described in detail in connection with **FIGS. 8-9** comprises a differential pulley ensemble with a hyperelastic shape memory alloy actuator. Calculations demonstrate that 1-4 kilograms of CuAlNi hyperelastic single crystal material can store and release the requisite amount of energy by means of the formation and reversion of stress-induced martensite as the crystal elongates and contracts as much as nine percent strain. Use of the differential pulley ensemble converts this linear displacement to rotary motion, providing a compact mechanical energy storage system.

[0028] CuAlNi single crystal provides a dense storage for kinetic energy in the form of crystal phase change. The force exerted is constant during excursion of a hyperelastic plateau during extension and contraction. The devices of the invention are characterized in that they: a) of modest weight, b) are of a size and shape practical for an individual/warfighter to carry and c) store enough energy to significantly boost jumping ability.

Physical Considerations: Mass (of the Individual and of the Device) and Energy Requirements

[0029] One example for employing a device in accordance with the invention is: (a) for use with a payload of 180 lbs (80 kg) and (b) for a jump height of 12 feet (4 meters). There is to be no external heating or cooling during the cycle. The design is for an energy storage device only. It is assumed that this device will be combined with additional specialized mechanical components for performance of specific tasks. The design may be scaled to larger or smaller dimensions, for example to provide a projectile launcher.

[0030] Assuming the 80-kilogram load and a jump height of 4 meters it is necessary that the mechanism store at least 3200 joules of energy. Shape memory alloys, which transform from one solid crystal structure to another, are capable of energy storage at greater densities than elastic materials. In hyperelastic transformations, the energy is absorbed and released at nearly constant force, so that constant acceleration is attainable.

Materials for Storing and Releasing the Required Energy

[0031] The preferred material for use as the energy store/release element in devices the invention is copper-aluminum-nickel single crystal hyperelastic alloy. CuAlNi sustains repeated strains of more than 9% as demonstrated in the stress-strain isotherm of **FIG. 1**. The plateau in the curve results from conversion of austenite high-temperature crystal structure to stress-induced martensite. The stress at which this plateau occurs increases with increasing temperature difference between the ambient temperature and the temperature austenite finish temperature (the temperature at which zero-stress thermal conversion from martensite to austenite is complete.) The rate is about 2 megapascals per degree C. Transition temperature is determined by composition. The ultimate tensile strength is sufficiently great that large strains are tolerated by an alloy having sub-zero (even cryogenic) transition temperature, allowing one to tune the mechanism characteristics to the application by varying the relative proportions of Cu, Al, and Ni.

[0032] Physical data for the preferred hyperelastic CuAlNi SMA are listed in Table I of **FIG. 10**

[0033] An example of one cycle of operation is as follows: a mass falls under influence of gravity and lands. Deceleration compresses a spring made of hyperelastic CuAlNi alloy. The alloy releases heat as the stress increases to the plateau and stress-induced martensite is formed. The alloy is then cooled (by external means) to its austenite finish temperature as the stress diminishes to zero. The spring is then returned to its original configuration. This cycle is depicted in **FIG. 2**.

[0034] During the deceleration phase of the cycle, i.e. Path (a) of **FIG. 2**), the temperature rises about 16 degrees C. as martensite is formed, latent heat is released, and 4 joules per gram of mechanical energy is stored. In Path (b) approximately 25 joules per gram of Cp-deltaT heat is removed from the crystal, driving its temperature to −10 degrees C., at which temperature the stress becomes negligible.

[0035] **FIG. 1** shows a stress-strain isotherm for a sample of CuAlNi having a transition temperature near 0 degrees C. From these data it can be shown that mechanical energy capacity is more than 4 joules per gram of CuAlNi alloy. Thus one kilogram of CuAlNi single crystal alloy can store enough energy to lift an 80 kg load to a height of 4 meters, or absorb the equivalent energy of descent.

[0036] **FIG. 2**. shows the stress-strain cycle for a free-falling mass that is stopped by a hyperelastic spring. At Path (a), stress increases to the plateau and strain increases as mechanical energy is absorbed and heat is released. During Path (b) the temperature is decreased to the Af temperature at which point the stress drops to zero. Finally, at (c) the material is returned to its original un-deformed state. These three thermodynamic path segments can be plotted on a three-dimensional model of the SMA as depicted in **FIG. 3**.

[0037] In **FIG. 3**. the schematic representation is of all possible thermodynamic paths in Nitinol titanium-nickel shape memory alloy. The three independent thermodynamic variables are force (or stress), length (or strain) and temperature.

[0038] In the chart of **FIG. 5**, polycrystalline TiNi **26** as shown by plot **26** is compared with single crystal CuAlNi as shown by plot **22**, both in the martensite phase.

[0039] In the chart of **FIG. 6**, polycrystalline TiNi **26** as shown by plot **24** is compared with single crystal CuAlN as shown by plot **20**, both in the austenite phase.

Differential Pulley Mechanism

[0040] The embodiment of **FIG. 4** provides a spring-loaded differential pulley mechanism. In its general concept, two pulleys having different radii are fixed to the same shaft. A single crystal SMA wire spring is anchored at the ends tangentially to the larger and smaller pulleys and form an arc over an idler pulley in such a way that as the pulleys rotate the wires are stretched in linear tension. The length of the spring and the diameters of the pulleys are selected so that as the pulleys are rotated through a specified angle the wires in the spring are strained nine percent. Energy stored in the spring is proportional to its mass, which is calculated to provide sufficient force and stroke for a pre-determined task. During the boost phase, as the spring contracts, the output torque is constant, providing a limited and constant acceleration. This output torque is conveniently converted to linear motion by a cable wound on a drum.

[0041] The differential pulley embodiment of **FIG. 4** comprises a dense energy storage device **80**. This device can be provided as a back-pack transportable unit employing the passive energy storing concept of the invention. Device **80** comprises a differential pulley set having a large diameter pulley **82** and small diameter pulley **84** keyed together for rotation on a common axle **86**. An idler pulley **88** is mounted for rotation on a second axle **90** which is positioned at a fixed distance from axle **86**. A length of wire **92** of single-crystal CuAlNi hyperelastic SMA has its proximal end **94** reeved on and affixed to the large pulley, its mid portion **96** reeved about the idler pulley, its distal end **98** reeved back and about the small pulley and then attached to a mass **99**.

[0042] In operation of device **80**, energy is stored by applying a downward stress on distal end **98**. The figure shows this step by using gravity on mass **99** to create the stress. Other means could be used to apply the stress, such as a small hand crank, not shown. The stress causes the paired pulleys **82**, **84** to rotate anticlockwise as viewed in the figure. The differential diameters of the two pulleys causes the SMA wire to elastically stretch and absorb energy. After stretching, the gear set could be locked against rotation by a suitable latch or detent, not shown, until energy release is desired. When the gear set is unlocked by the user, the wire contracts and releases the energy as the gear set rotates clockwise. The released energy could be employed to do work, such as by using the rotating axles **86** and/or **90** to rotate a cutting tool, drill or the like.

Technical Design: Calculations, Dimensions, Forces, Strength of Materials.

[0043] Table II of **FIG. 11** shows calculations for the technical parameters in one example of the differential pulley mechanism of **FIG. 4**.

[0044] This table uses the equations of motion of a differential pulley system to calculate physical sizes of the components, and to keep these within reasonable limits. Many possible solutions can be calculated that meet the stated goals, but not all are practical.

[0045] Two cases are presented, each capable of delivering 3200 joules of mechanical energy. Each has been derived to produce a half turn of the pulley assembly. In the first case, having a stroke of 4 meters and a lifting force of 80 kg, the cable is wound on a drum that is too large to be practical. In the second case, the stroke has been reduced by one half, and the lifting force doubled. This results in a drum radius that is reasonable for being carried in a back-pack. This design presumes that the application will contain a lever arm to increase the stroke by a factor of two.

Knee Hinge Device

[0046] In the embodiment of **FIG. 8** and **FIGS. 9A-9B** knee hinge device **100** is provided for human locomotion, such as vaulting. On each leg of the user pairs of braces **102** and **104** are secured on each side of the knee by respective bands **106** and **108** which are wrapped around the respective upper portion of the calf and lower portion of the upper leg. A length of hyperelastic SMA wire **110** is secured at its opposite end **112** and **114** to respective braces **102** and **104**. The mid portion of the wire is reeved about the curved sector **116** of brace **104** to serve as a pulley for directing the pulling forces of the wire along the lengths of the respective braces. This geometry results in sequential stretching and contraction of the SMA wire as the knee flexes

[0047] **FIGS. 9A, 9B**, 9C, 9D, 9E and 9F show the human wearing a pair of the hinge devices **100**, **101** with the elements in sequential positions throughout a vaulting cycle.

[0048] During operation, as the person's legs stride forward before a launch, one knee flexes by bending so that the thigh and calf pivot toward each other. The weight and forward momentum of the person causes SMA wire **110** to stretch during the flexing and store energy. As the person's weight is shifted to the other leg and momentum is lost, the wire contracts and releases most of the stored energy, causing the knee to flex back and straighten the leg while forcefully propelling the person forward and/or up.

Pogo Stick Device

[0049] **FIGS. 12 and 13** illustrate a pogo stick device **210** in accordance with another embodiment. Device **210** comprises a cylindrical body **212** having a lower end **214** that is formed with an opening **216** which slidably carries a strut **218**. A pair of foot pedals **220**. **222** are mounted on the lower end of the strut. A handle **224** is mounted on the upper end of the body. A wire or rod **226** of single crystal hyperelastic SMA is mounted at one end with the upper end of the strut. The wire's other end is mounted to the lower end **214** of the body.

[0050] **FIG. 12** shows the relative positions of the body and strut when not subjected to axial forces with wire **226** unstressed. **FIG. 13** shows the positions when the strut has moved up relative to the body while stretching the wire and storing energy during one phase of the pogo cycle of operation. The wire releases the energy as it contracts and moves the elements (as the human riding the pogo) back to the positions of FIG. **12**.

Technical discussion of CuAlNi Single Crystal Hyperelastic Alloy: Why it is Superior, How it Works, and How it is Made.

[0051] Hyperelastic shape memory alloys comprise an enabling technology providing dense energy storage, constant force, and simple implementation. Conventional elastic spring material may be strained about 0.5 percent without permanent deformation. In contrast, mechanical energy is stored by a crystalline phase change in hyperelastic SMA, allowing complete recovery of more than 9 percent, a twenty-fold increase. Deformation and recovery take place at constant stress so that forces and hence accelerations are limited and predictable.

[0052] Conversion of high-temperature crystalline phase to stress-induced martensite permits a very large amount of mechanical energy to be stored, and, as the single crystal is not plastically deformed, complete shape recovery takes place at nearly the same level of stress.

[0053] This material is created by pulling single crystals from melt in a process known as the Stepanov method, similar to the Czochralski method of fabricating silicon boules for microelectronics manufacture.

Background of Hyperelastic Shape Memory Alloys

[0054] SMA materials have become popular for use as actuators due to their ability to generate substantial stress during shape recovery of large strains during temperature-induced phase transformation. The energy density of such actuators is high compared to other alternatives, such as electromagnetic, electrostatic, bimetals, piezoelectric, and linear

[0055] and volume thermal expansion effects of ordinary materials. The operating cycle of an SMA actuator includes deformation during or after cooling, and subsequent heating which results in a temperature-induced phase transformation and recovery of the deformation. SMA actuation is favored where relatively large force and small displacements are required in a device that is small in size and low in mass.

[0056] Shape memory is the ability of certain alloys to recover plastic deformation, which is based on a diffusionless solid-solid lattice distortive structural phase transformation. The performance of shape memory alloy based actuators strongly depends on the amount of recoverable deformation. In turn, recoverable deformation itself is a function of the lattice distortions which take place during martensitic phase transformation in the particular SMA. For an individual grain (single crystal) of SMA, the amount of possible recoverable strain after uniaxial loading, depends on the particular crystallographic orientation of the deformation tensor relative to the crystallographic axes of the high temperature (austenite) phase and the sign of applied load (tension or compression).

[0057] For a given deformation mode, the recoverable strain is strongly orientation dependent, and for the various crystallographic directions it differs by approximately a factor of two.

[0058] The recoverable deformation of these polycrystalline SMA alloys, due to the lattice distortion during diffusionless solid-solid phase transition, is substantially lower than is theoretically possible for a given material. The main reason for this is that for a conglomerate of randomly oriented grains (as is normally the case for polycrystalline materials), the average deformation will always be less than the maximum available value for a given grain. The diffusionless nature of phase transitions in SMA results in strict lattice correspondence between the high temperature (austenite) and low temperature (martensite) lattices. As the symmetry of the martensite lattice is lower than that of austenite, maximum deformation in each grain can only be attained in one particular crystallographic direction. This means that for randomly oriented grains (as normally is the case for polycrystalline materials), the average deformation will be at least a factor of two less than the maximum.

[0059] The restrictions imposed on a polycrystalline body by the deformation mechanism is another reason for diminished recoverable deformation in polycrystals as compared with a single crystal. To maintain integrity of the polycrystal, deformation of each particular grain has to be less than that corresponding to the theoretical limit for lattice distortion.

[0060] Therefore, for polycrystalline material, resultant recovery is the vector sum of particular grain deformations over the whole range of grain orientations, and is significantly smaller than the maximum value for an individual single crystalline grain.

[0061] By comparison, recoverable deformation close to the theoretical value (lattice distortion) can be achieved in single crystalline SMA. In addition to the substantially increased recoverable deformation, absence of grain boundaries results in increased strength and longer fatigue life. Specifically, as a single crystal, the strength of the grain for CuAlNi SMA can be as high as 800 MPa with the practical limit for recoverable deformation up to 9 percent and potentially even higher for special deformation modes. An additional advantage of a single crystal SMA is that not only the thermally induced phase transformation may contribute to the recoverable deformation, as in the case for polycrystals, but also stress-induced martensite-to-martensite phase transitions. Depending on the material, this additional contribution may be up to 15 percent. Therefore the total theoretical recovery can be as high as 24 percent.

[0062] The graphs of FIGS. **6**(*a*) and **6**(*b*) show stress-strain curves for a CuAlNi single crystal SMA and a polycrystal TiNi SMA. Curve **20** shows the single crystal SMA in its austenitic phase while curve **22** shows the martensitic phase. Curve **24** shows the polycrystal SMA in its austenitic phase while curve **26** shows the martensitic phase.

[0063] Hyperelastic single crystal SMA is an enabling technology for mechanical energy storage. It has the following advantages over polycrystal SMA for mechanical devices:

[0064] 1. Large strain recovery. In **FIG. 6** the region **28** of curve **22** for the austenitic phase of the single 'hyperelastic' SMA shows the magnitude of its strain recovery in comparison to the comparable region **30** of curve **26** for an austenitic polycrystal SMA. There is a three-fold gain in performance over the conventional SMA materials made from bulk materials, such as TiNi. Depending on how the sample is used, the great strain recovery can either be used in the high temperature state as a spring, for example, or deformed when in martensite phase and then heated to recovery as an actuator.

[0065] 2. True constant force deflection. Unlike polycrystalline materials which reach their strain/stress plateau strength in a gradual fashion and maintain an upward slope when deformed further, hyperelastic SMA materials have a very sharp and clear plateau strain/stress that provides a truly flat spring rate. This is shown in **FIG. 6** by the region **32** of curve **20**. The stress level at which the plateau occurs depends on the temperature difference between the transformation temperature and the loading temperature. Additionally, single crystal SMAs exhibiting hyperelasticity benefit from a second stress plateau which can increase the total recoverable strain to 24 percent.

[0066] 3. Very narrow loading-unloading hysteresis. As a result there is substantially the same constant force spring rate during both loading (increasing stress) and unloading (decreasing stress). This is shown in **FIG. 6**

by the narrow vertical spacing **34** between the upper portion of curve **20** which represents loading and the lower portion representing unloading. This characteristic is key in applications where the flexure undergoes repeated cycling. In comparison, there is a relatively wide spacing between the corresponding loading and unloading portions of curve **24**.

[0067] 4. Recovery which is 100 percent repeatable and complete. One of the drawbacks of polycrystalline SMA materials has always been the 'settling' that occurs as the material is cycled back and forth. This is shown in **FIG. 6** for curve **24** by the spacing **36** of the curve end representing the beginning of the loading and the curve end representing the end of the unloading. The settling problem has required that the material be either 'trained' as part of the manufacturing process, or designed into the application such that the permanent deformation which occurs over the first several cycles does not adversely affect the function of the device. By comparison, hyperelastic SMA materials do not develop such permanent deformations and therefore significantly simplify the design process into various applications. This is shown in **FIG. 6** where the beginning of curve **20** representing unloading coincides with the end of the curve representing loading.

[0068] 5. Very low yield strength when martensitic. This property is shown by the horizontal portion **38** of curve **22**, which is relatively much lower than the corresponding portion of curve **26**. The property is key for designing an SMA actuator which is two way (i.e., it cycles back and forth between two states). This is typically done by incorporating a biasing element, which overcomes the SMA when cold or martensitic, and establishes position one until the SMA is heated and overcomes the biasing element for driving the mechanism to position two. The problem with this type of device when using polycrystalline SMA is that the biasing element robs a significant amount of work output from the SMA. By comparison, an equivalent hyperelastic SMA element has a much lower yield strength when martensitic, enabling a much softer biasing element, and therefore generating a much greater net work output.

[0069] 6. Ultra-low transition temperature. Hyperelastic SMA materials made from CuAlNi can be manufactured with transition temperatures near absolute zero (minus 270 Celsius). This compares to SMA materials made from TiNi which have a practical transition temperature limit of −100 Celsius.

[0070] 7. Intrinsic hyperelastic property. TiNi SMA can be conditioned, through a combination of alloying, heat treatment and cold working, to have hyperelastic properties. Single crystal CuAlNi SMA has intrinsic hyperelastic properties: a crystal of CuAlNi is hyperelastic immediately after being formed (pulled and quenched) with no further processing required.

Method of Fabricating Single Crystal SMA

[0071] Since single crystals cannot be processed by conventional hot or cold mechanical formation without breaking single crystallinity, a special procedure is required for shaping single crystals in the process of growth as the crystal is pulled from melt, resulting in finished shape.

[0072] Single crystal SMA is fabricated in a special crystal-pulling apparatus. A seed of the desired alloy is lowered into a crucible containing a melted ingot of the alloy composition, and gradually drawn up. Surface tension pulls the melted metal along with the seed. The rising column cools as it leaves the surface of the melt. The rate of drawing is controlled to correspond with the rate of cooling so that a solid crystal is formed at a region that becomes a crystallization front. This front remains stationary while the crystal, liquid below and solid above, travels through it. The top surface of the melt can contain a die (of the desired cross-sectional shape) that forms the shape of the crystal as it grows. This procedure generally is known as the Stepanov method of making single crystals. The principal elements are shown in **FIG. 7**.

[0073] After the ingot is melted the crucible with the metal is lifted up until the hydrostatic pressure pushes the molten metal almost to the upper edge of the shape-forming die. The metal should be overheated above the melting point for about 10-15 C. After the temperature becomes stable the seed is lowered into the die opening until it reaches the surface of the molten metal. This operation requires a port for visual observation. The seed material melts and the column of molten metal confined by the capillary forces rises above the upper edge of the shape-forming die. The combination of the proper pressure (defined by the vertical position of the crucible), metal temperature (defined by the power applied to the heater) and capillary forces will maintain the corresponding shape of the molten material and at the same time prevent it from spilling. Now the pulling mechanism is turned on and the seed starts moving up, away from the shape-forming die. The column of molten material becomes longer until its length gets stabilized with the crystallization front at the top few millimeters above the edge of the shape-forming die. Continuous adjustment of pressure and temperature is needed to stabilize the shape of the molten column of the metal for a given pulling rate.

[0074] The shape and size of the single crystal produced according to method described above are defined by the geometry of the shape-forming die, the pressure of liquid at the edge of the shape-forming die, and the position of the crystallization front relative to the shape-forming die. There is no specific physical limitation on the length of the pulled single crystal. However, technically it is limited by the stroke of the pulling mechanism.

[0075] From the known Cu—Al phase diagram, rapid cooling (quenching) of the drawn crystal is necessary for production of single crystal beta phase that has the desired hyperelastic properties. Starting with beta phase at 850-1000 Celsius, if the alloy is cooled slowly the beta phase precipitates as beta+gamma, and at lower temperatures, as alpha+gamma−2. Single crystal beta phase, which requires that Al remains in solution at room temperature, is formed by rapid cooling in salt water from 850 Celsius. At elevated temperatures, above 300 Celsius, some decomposition gradually occurs; in fact, beta phase is not entirely stable at room temperatures but the time constant for decay is many years. The known phase diagram for the ternary CuAlNi alloy has similar characteristics.

1. An energy storage device comprising a hyperelastic shape memory alloy element which changes to one shape while storing energy responsive to a stress, and a structure which applies the stress to the element, the structure being selected from the group consisting of a differential pulley mechanism, a knee brace and a pogo stick.

2. A device as in claim 1 in which the hyperelastic element is a single crystal.

3. A device as in claim 1 in which the hyperelastic element is a single crystal of copper aluminum nickel.

4. A device as in claim 3 in which the alloy contains about 80% Cu, 12% Al, and 3% Ni by weight.

5. A device as in claim 1 in which the pulley ratio of the differential pulley is about 4/3.

6. A device as in claim 1 in which the hyperelastic element elongates by more than 8 percent strain responsive to the stress

7. A method of storing and selectively releasing energy in a device that can be carried by an individual, the method comprising the steps of providing a hyperelastic shape memory alloy element, applying a stress to the element which stores energy in the element which when release is sufficient to enable the individual to undertake superior performance in locomotion and other physical activities, and releasing the energy.

8. A method as in claim 7 in the step of applying the stress is carried out by elongating the element while storing energy, and the step of releasing the energy is carried out by enabling the element to contract.

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