

Octa-Anchor Radial Web and Point-Actuation: Synergistic Design Principles for Shape Memory Alloy Spatial Protection

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Abstract

This paper systematically presents two spatial protection principles from the Stiffness-Switching paradigm – the “Octa-Anchor Radial Spatial Web” (Principle 2) and “Point-Actuation Perimeter Absorption” (Principle 3) – including their physical foundations, design methods, and cross-domain applications. Principle 2 uses an isotropic radial pre-tension network formed by eight corner anchors to decompose omnidirectional impact forces into axial tension in multiple SMA wires, solving the problem of force distribution. Principle 3 uses discrete point load nodes to convert a concentrated impact into lateral stretching of an SMA mesh, solving the problem of energy transformation. Together, the two principles form a complete spatial protection system that ranges from macro-scale force decomposition to micro-scale energy dissipation. Four case studies – a protective container, a spacecraft landing buffer, hand protection (industrial anti-vibration gloves and sports cycling gloves), and an SMA flexible bulletproof/stab-resistant liner – cover precision instrument protection, aerospace engineering, industrial health, sports protection, and personal armour, demonstrating the universality of the two principles. The paper further explores progressive applications of SMA cellular structures in spatial protection, from the layer-by-layer buckling of 2D honeycombs to the rolling energy dissipation mechanism of 3D spherical honeycombs, as a long-term extension of the paradigm. Small structures, big functions – from a single SMA wire to a landing field that catches a re-entry capsule, the simplification in spatial protection is always in progress.

Keywords: Shape memory alloy; octa-anchor; radial spatial web; point actuation; impact protection; superelasticity; energy absorption; cellular structure; cycling protection

1. Introduction

Injury reduction and protection are the professional instincts of a physician. When this protective instinct extends into engineering, an age-old question emerges: how can we keep precision instruments undamaged during transport? How can we prevent a re-entry capsule from being crushed at touchdown? How can a lunar rover drive safely on an unknown surface?

Impact protection is the common answer to these questions. Conventional solutions fall into three categories. Foam materials offer acceptable energy absorption but are single-use and suffer from bottoming out. Aluminium honeycombs absorb energy efficiently out-of-plane but are highly directional and also non-reusable. Hydraulic or pneumatic dampers can be reused, but they depend on seals, a power supply, and complex control, limiting their reliability in extreme environments such as space. The common limitation of these approaches is that they sacrifice either reusability, omnidirectional uniformity, or reliance on external energy and control.

This paper argues that the superelastic plateau of shape memory alloys (SMA) provides a physical foundation to overcome these limitations. During stress-induced martensitic transformation, SMA can absorb a large amount of mechanical energy at an almost constant stress level, converting kinetic energy into heat. After unloading, the stress-induced martensite transforms back spontaneously and the material recovers its original shape. This means that an SMA-based protection device can simultaneously achieve fully passive energy absorption, self-reset, and

reusability.

However, material properties alone do not constitute a complete protection solution. In real engineering, impact directions are arbitrary and the forms of impact forces vary with the scenario. Therefore, this paper extracts two design principles specifically for spatial protection from the Stiffness-Switching paradigm. Principle 2, the “Octa-Anchor Radial Spatial Web”, uses eight corner anchors to create an isotropic radial pre-tensioned network that decomposes any directional impact into axial tension of multiple SMA wires – solving “where the force goes”. Principle 3, “Point-Actuation Perimeter Absorption”, uses discrete point load nodes to convert a concentrated impact into lateral stretching of the surrounding SMA mesh – solving “how the force is transformed”. The synergy of the two principles gives a complete spatial protection system from macro-scale force decomposition to micro-scale energy dissipation.

The purpose of this paper is to elevate these two principles from the design experience of a single protective container into a universally applicable design methodology for spatial protection. Through four cross-domain case studies – a passive multi-level impact protective container, a spacecraft landing buffer, hand protection (including industrial anti-vibration gloves and sports cycling gloves), and an SMA flexible bulletproof/stab-resistant liner – we systematically describe the mechanical models, design elements, and synergistic mechanisms, providing a unified physical solution for impact protection ranging from precision instruments to human body protection.

2. Physical Basis: Two Core Problems of Spatial Protection

The physical essence of impact protection is to convert kinetic energy into other forms of energy within an extremely short time window while limiting the peak acceleration experienced by the protected object. For omnidirectional impact protection – where the direction of impact cannot be predicted – this task can be broken down into two sub-problems: how to efficiently transmit an arbitrary directional impact to the energy-absorbing elements (force decomposition), and how to efficiently convert a concentrated impact force into heat energy (force transformation). Principle 2 and Principle 3 address these two sub-problems respectively, based on the SMA superelastic plateau.

2.1 Principle 2: Octa-Anchor Radial Spatial Web – How Force Is “Shared”

The structural inspiration for this principle comes from the mechanics of spatial suspension – imagine an object suspended at the centre of a space by multiple ropes tensioned from different directions (like Spider-Man’s web-slinging suspension). Any displacement in one direction is restrained by the ropes on the opposite side. Each of the eight ropes bears only uniaxial tension, but when they work together, the suspended object is in equilibrium in all directions.

The core idea of Principle 2 is to take the geometric centre of the protected object as the origin, arrange anchors at the eight corners of the protective shell, and make the tension lines of all SMA elements converge towards the centre, forming an isotropic radial spatial pre-tensioned web.

This structural design achieves force decomposition through three levels. At the geometric level, the eight corner anchors are placed at the vertices of a 3D space, and the tension direction of each SMA element points toward the geometric centre. No matter from which direction an impact comes, at least two SMA elements are colinear (or nearly so) with the impact direction and can directly bear the force, while the other elements provide lateral restraint to prevent the protected object from deviating from the centre. This ensures isotropic omnidirectional protection – for an impact from any direction, there will always be SMA elements responding

along its line of action.

At the mechanical level, when the impact force acts on the shell and is transmitted to the protected object, the object's displacement stretches the SMA elements in the impact direction. In conventional foam protection, the impact force is absorbed over an area and the force varies with foam density and compression. In the present web, the impact force is decomposed into axial tension in multiple SMA wires. Each wire independently enters the superelastic plateau region and absorbs energy at an almost constant force. The kinetic energy of the impact is distributed among several SMA wires and dissipated separately, rather than being concentrated in a single element. From the viewpoint of force balance, the tensions of all SMA wires cancel out under static conditions, suspending the protected object at the centre; when an impact occurs, the wires in the impact direction are stretched and their tension dynamically balances the impact force.

At the resetting level, after the impact, all stretched SMA wires recover elastically and work together. Because the superelastic recovery force of each wire points toward the geometric centre, the protected object automatically returns to the central equilibrium point under the action of the restoring forces. This automatic resetting mechanism eliminates the risk of secondary collision that may occur with conventional protection – the object does not bounce around inside the container.

For the common multi-point anchor configuration (8 corners, 6 face centres), Principle 2 recommends giving priority to the octa-anchor (corner) scheme. The force decomposition efficiency of the corner anchors is comparable to that of the face centre anchors, but the corner arrangement makes better use of the structural strength of the shell corners and avoids adding extra anchoring structures on the face centres. For very valuable or fragile objects, auxiliary anchors can be added at the face centres to form an 8+6 enhanced scheme.

It should be noted that configurations that suspend an object at the spatial centre using multiple diagonal cables or links to provide omnidirectional restraint have been used in existing engineering – for example, the six-degree-of-freedom Stewart platform uses six parallel links for omnidirectional positioning, and tuned mass dampers in building structures use cables to suspend a mass. However, those solutions rely on active control, hydraulic or electric drives. The innovation of Principle 2 lies in replacing rigid links or steel cables with SMA superelastic wires, so that the whole network simultaneously accomplishes force decomposition, energy absorption, and resetting in a fully passive manner.

2.2 Principle 3: Point-Actuation Perimeter Absorption – How Force Is Transformed

The inspiration for this principle comes from the paw pads of felines – when jumping and landing, the pads contact the ground first and absorb impact through compression of the soft tissue. But after adding an SMA mesh, the energy absorption mechanism is fundamentally changed.

The core idea of Principle 3 is to use discrete point load nodes to distribute a concentrated impact force over a surface-like energy-absorbing layer, while simultaneously driving the surrounding SMA mesh into lateral tension that enters the superelastic plateau, achieving a “vertical-force-driven lateral energy absorption” synergy.

The physical realisation relies on two key elements. The first is a biomimetic cushion layer made of a multi-chamber elastomer that mimics the cushioning mechanism of feline paw pads. When an impact force acts on a point load node, the cushion layer is compressed, its internal chambers collapse stepwise, and high-frequency micro-vibrations are dissipated through viscoelastic

deformation. More importantly, the compression of the cushion layer forces the material to expand laterally, and this lateral expansion activates the second energy absorption mechanism. The second mechanism is the lateral stretching of the SMA mesh. The SMA mesh is pre-stretched to the start of the superelastic plateau and attached to the surface of the cushion layer. When the cushion layer expands laterally due to the impact, the SMA mesh is stretched along with it, and the mesh cells in the region around the impact point undergo lateral deformation, entering the superelastic plateau. During this process, the stress-induced martensitic transformation converts the mechanical work of the impact into heat. This “vertical-force-driven lateral energy absorption” mechanism transforms the direction of the force – the impact force originally acts perpendicular to the loaded surface, but the energy absorption occurs in a plane perpendicular to the impact direction. This means that energy absorption is not limited by the direction of the impact force; regardless of the incidence angle, as long as the force acts on a point load node, the surrounding SMA mesh will be stretched laterally.

2.3 Synergy of the Two Principles

Principle 2 builds the “skeleton” of force decomposition, and Principle 3 builds the “muscle” of force transformation. They work together: the web decomposes impact forces from various directions and directs them into axial stretching of multiple SMA wires, while the composite cushion converts the concentrated force at the point of entry into lateral energy absorption and simultaneously dissipates residual high-frequency vibrations. The former ensures the structural integrity of omnidirectional protection, and the latter enhances the energy attenuation efficiency for a single point impact.

From a thermodynamic viewpoint, the whole protection process converts mechanical work into heat. In both Principle 2 and Principle 3, the stress-induced martensitic transformation of the SMA wires consumes mechanical work and converts it into latent heat of transformation. After the impact, the heat is gradually dissipated through heat conduction along the SMA wires and convection of the surrounding air. This passive dissipation mechanism requires no external cooling or energy recovery, relying entirely on the material’s own physical properties.

3. Case Studies: Four Cross-Domain Applications

3.1 Case 1: Passive Multi-Level Impact Protective Container

Precision medical instruments, high-value scientific samples, and aerospace components face omnidirectional impact risks during transport and handling. Conventional foam liners suffer from bottoming out and are single-use, while hydraulic damping systems are complex and require external power.

The protective container uses Principle 2 as its macro-scale protection framework and Principle 3 as the local energy absorption supplement. On the inner walls of an aluminium alloy rectangular container, slots are provided at the eight corners to receive the ends of several constant-force SMA straps. Each strap contains a NiTi superelastic wire pre-stretched to the start of the superelastic plateau and coated with a silicone anti-slip layer. The straps are arranged in both cross and diagonal patterns, suspending the protected object at the centre of the container. Under normal transport vibrations, small displacements of the object cause the SMA wires to move within their elastic range while maintaining a constant-force suspension. When an impact occurs, the straps in the impact direction are stretched further into the superelastic plateau, and the stress-induced martensitic transformation converts the kinetic energy of the impact into heat.

On the six faces of the container, convex SMA biomimetic composite buffer modules are attached to the inner wall. Each module consists of an SMA mesh covering a biomimetic “cat paw” cushion layer, and a ring-shaped deformation space is reserved around each module. The SMA mesh is pre-stretched to the start of the plateau. When an impact force is transmitted to a module, the SMA mesh is first stretched at the contact point and enters the superelastic plateau to absorb energy; simultaneously, the cushion layer is compressed and expands laterally, driving the surrounding SMA mesh also into the plateau. The multi-chamber structure of the cushion layer dissipates high-frequency micro-vibrations through viscoelastic deformation.

After the impact, all straps recover elastically together, returning the object to the central equilibrium point and eliminating secondary collisions. The SMA mesh also recovers its original shape due to superelasticity, restoring the buffer module. Under non-extreme conditions, the whole system is completely reusable. The straps are available in three standardised series (light, medium, heavy load) according to their tension capacity, so that users can choose them based on the weight and fragility of the object. Each strap is an independently replaceable module; if damaged or degraded, it can be replaced individually without discarding the entire container.

Eight points balance a space. An impact from any direction is decomposed into axial tension.

3.2 Case 2: Spacecraft Re-entry Capsule Landing Buffer and Planetary Lander Leg

The moment of landing of a re-entry capsule or a planetary lander involves a short-duration, high-overload impact. Conventional aluminium honeycomb or airbag solutions are mostly single-use, while hydraulic dampers require complex sealing and control systems, limiting their reliability in deep space environments. This case study is presented in a progressive manner.

Level 1: SMA biomimetic composite buffer module on the landing leg (Principle 3)

A conventional honeycomb block on the landing leg is replaced by an SMA biomimetic composite buffer module based on Principle 3. The module comprises an SMA mesh covering a multi-chamber biomimetic material. At touchdown, the SMA mesh at the contact point is first stretched into the superelastic plateau to absorb energy; the biomimetic material is compressed and expands laterally, driving the surrounding SMA mesh also into the plateau – vertical impact drives lateral energy absorption. After the impact, the SMA mesh recovers its shape due to superelasticity, ready for any secondary rebound.

Compared with conventional solutions, the SMA buffer module offers the advantage of nearly constant-force energy absorption. The force-displacement curve of aluminium honeycomb shows considerable fluctuation and a sharp rise after bottoming out, whereas the SMA mesh operates at an almost constant stress within the plateau, providing a smoother deceleration and more precise control of the acceleration peak experienced by the protected object.

Level 2: Internal payload protection (synergistic application of Principle 2)

The landing leg modules handle external impact, but after the impact force is transmitted inside the lander, delicate scientific instruments still require additional protection. A feasible concept is to mount the instruments rigidly on a common platform, which is then connected to the lander shell by the octa-anchor radial web of Principle 2 – the platform is suspended from the eight corner anchors by multiple SMA constant-force straps. During landing, the platform undergoes a small displacement relative to the shell, stretching the straps in the impact direction into the superelastic plateau; after the impact, the straps recover together and the platform resets automatically.

It should be noted that this concept is mainly applicable to scenarios where “post-impact

resetting” is required and where a controlled displacement of the instruments during the impact is acceptable. For precision optical instruments that must remain absolutely rigidly fixed, traditional rigid connections are still necessary. This concept is presented as a synergistic application of Principle 2 in aerospace protection, leaving its detailed engineering feasibility for future design verification.

Level 3: From single module to landing field array (engineering scale-up of Principle 3)

A single SMA biomimetic buffer module is about the size of a palm, but when dozens of such modules are arranged in an array on the bottom of a re-entry capsule, they form a landing buffer system capable of handling a single return mission. However, we believe that the engineering potential of Principle 3 goes even further.

A more advanced design concept is to cover a pre-defined landing area on the ground with tens of thousands of SMA biomimetic buffer modules, forming a large permanent landing field. The module array covers the entire landing error ellipse – from the high-probability central area out to the low-probability edges. Wherever the capsule touches down, it always contacts an SMA buffer module, whose protection performance is superior to conventional single-use aluminium honeycomb or untreated hard ground.

The engineering advantages of this concept are many. In terms of buffer performance, the constant-force plateau of SMA provides a smoother deceleration than aluminium honeycomb. In terms of redundancy, the large array naturally offers extreme fault tolerance – the capsule contacts only a few modules at touchdown (typically 3-5), and if a single module is damaged, only that module is affected. In terms of maintainability, after a mission only the damaged modules need to be inspected and replaced. In terms of passivity, the entire landing field requires no sensors, no active control system, and no external power – wherever the capsule lands, the SMA modules there are triggered to absorb energy.

Eight points balance a space. A palm-sized module, when arrayed, can catch an entire re-entry capsule.

Level 4: Long-term perspective – progressive applications of SMA cellular structures

The above SMA biomimetic composite buffer modules are a direct application of Principle 3 for landing buffering. SMA cellular structures offer further optimisation possibilities.

Begin with 2D hexagonal honeycomb. Under out-of-plane compression, the cell walls buckle layer by layer – the outer layer cells first enter the superelastic plateau and absorb energy through stress-induced martensitic transformation; after they have collapsed, the next layer takes over. This layer-by-layer buckling naturally creates graded damping: weak impacts activate only the outer cells (gentle damping), while strong impacts mobilise all cells (strong damping).

Upgrading to 3D space-filling honeycombs (e.g., Kelvin structure, truncated octahedra) removes the directionality of conventional 2D honeycombs. Cells have continuous wall networks in all three orthogonal directions, so whether the impact is axial, lateral, or oblique, there are walls that undergo buckling to absorb energy.

A further conceptual step is the radial annular composite honeycomb, inspired by traditional millstone patterns. The upper and lower stones of a mill are engraved with radial grooves and concentric circular grooves. Whatever direction the grain enters the gap, it is captured and ground by the grooves. Mapping this topology to an SMA cellular structure: cell walls are arranged radially (radial ribs) together with circumferential stiffening rings at different radii. The radial ribs absorb radial impacts (compression in the tyre-ground contact region), while the

circumferential rings absorb tangential impacts (e.g., side-slip shear) and convert part of the shear into tension/compression of the radial ribs. By optimising the density of radial ribs (sparser from the centre outward to match the pressure distribution in a tyre contact patch) and the spacing of the rings, an isotropic energy absorption topology can be achieved in the plane.

Manufacturing such structures relies on additive manufacturing of SMA – printing the integrated radial annular honeycomb layer by layer without welding or assembly. Compared with 3D space-filling honeycombs, the radial honeycomb achieves in-plane isotropic energy absorption, making it more suitable for applications such as tyres, where radial load dominates and tangential load is secondary.

From an extruded prism to a millstone pattern – the topology of the honeycomb determines the direction of energy absorption. Force programming – I need a force, and it is there.

This concept is presented as a long-term extension of Principle 3 for extreme impact energy scenarios, to be explored in future research.

3.3 Case 3: Hand Protection – Industrial Anti-vibration Gloves and Sports Cycling Gloves

The protection requirements for hands in industrial and sports environments differ substantially, but they share the same physical principle – the point-actuation energy absorption mechanism of Principle 3. This case study presents two application scenarios. Both share the physical mechanism of Principle 3 but differ in design parameters according to the energy spectrum of the impacts.

3.3.1 Industrial anti-vibration gloves: continuous vibration and occasional impact

In industrial environments, equipment such as hand-held power tools, pneumatic hammers, and chainsaws generate high-frequency vibration and occasional impacts, causing cumulative hand injuries (e.g., white finger disease). Traditional anti-vibration gloves rely on foam or gel pads, which have limited vibration attenuation and significantly reduce hand dexterity.

The graded damping anti-vibration glove embeds SMA biomimetic composite buffer modules at key force-bearing areas on the palm and back of the hand. Each module has the same configuration as the buffer module in the protective container – an SMA mesh covering a multi-chamber biomimetic material. Under normal tool gripping, the SMA mesh conforms to the skin with a preset constant force, and the biomimetic material provides basic vibration isolation. The continuous high-frequency micro-vibrations generated by the tool are dissipated by the multi-chamber structure through viscoelastic deformation, while the SMA mesh moves within its elastic range and does not affect operational dexterity. When an occasional impact occurs, the impact force is transmitted to the buffer module, triggering the synergistic energy absorption mechanism of Principle 3 – the SMA mesh enters the superelastic plateau, the biomimetic material is compressed and expands laterally, driving the surrounding mesh also into the plateau.

3.3.2 Sports cycling gloves: impact protection against falling

In cycling, falling onto the outstretched hand is a common injury mechanism. The impact force is highly concentrated on the thenar, hypothenar, and the radial/ulnar sides of the wrist, potentially causing scaphoid fractures, distal radius/ulna fractures, triangular fibrocartilage complex injuries, etc. Traditional cycling gloves rely on foam or silicone pads, which have limited energy absorption for moderate to high-speed impacts, and excessive pad thickness affects handlebar feel.

Based on Principle 3, this paper proposes a conceptual design of an SMA flexible cushioning cycling glove. The buffer modules are preferentially placed at the mechanical load-bearing points on the thenar, hypothenar, and the radial/ulnar sides of the wrist – the main contact points

between the palm and the ground when falling. Each module consists of an SMA mesh covering a multi-chamber biomimetic material, with a deformation space reserved around it. The modules are attached to the inner fabric layer of the glove by heat pressing and covered with a breathable mesh to prevent detachment.

During normal cycling, the contact between palm and handlebar is a continuous low-pressure contact. The SMA mesh conforms to the hand within its elastic range with a preset low force, and the biomimetic material provides basic comfort cushioning. The module thickness is controlled to 3-5 mm and they are placed only at specific nodes rather than over the whole palm, so handlebar feel is largely unaffected. When the cyclist falls, the hand hits the ground at a relatively high speed. The impact force is transmitted to the buffer modules, triggering the Principle 3 mechanism – the SMA mesh enters the superelastic plateau, converting the impact kinetic energy into heat via stress-induced martensitic transformation; the biomimetic material is compressed and expands laterally, driving the surrounding SMA mesh into the plateau; the internal chambers dissipate residual energy through viscoelastic deformation.

The following table compares the two glove types:

Design parameter	Industrial anti-vibration glove	Sports cycling glove
Module distribution	Palm + finger pads + back of hand	Thenar + hypothenar + radial/ulnar wrist
Main working condition	Continuous high-frequency vibration + occasional impact	One-time fall impact
Preset plateau force	Matched to grip force	Matched to body weight and impact speed

The industrial glove handles “long-duration small vibrations” and requires higher sensitivity and medium-hard feedback; the cycling glove handles “short-duration large impacts” and requires softer static touch and a higher dynamic energy absorption threshold. The physical principle is the same, only the design parameters differ – demonstrating the universality of Principle 3 across different energy spectra.

Compared with traditional cycling glove pads, the SMA cushion module offers the key advantage of being soft and comfortable during normal riding while automatically entering the superelastic plateau on impact, providing a smooth deceleration for the palm. After the impact, the SMA mesh recovers its original shape and the glove can be reused.

Force at a point drives surrounding energy absorption. It fits softly during a ride, and silently catches you when you fall.

3.4 Case 4: SMA Flexible Bulletproof / Stab-Resistant Liner

Conventional bulletproof vests rely on stacked layers of high-performance fibres (e.g., Kevlar) that dissipate bullet kinetic energy through fibre breakage and inter-layer friction. However, they have inherent limitations: high rigidity, reduced wearer mobility; poorer protection against stabbing (low speed, high local pressure) than against bullets; and the buffer layers are mostly single-use – the whole vest may be discarded after being hit.

Based on the point-actuation mechanism of Principle 3, this paper proposes a conceptual design

of an SMA flexible bulletproof/stab-resistant liner. The liner consists of three integrally formed gradient layers:

- **Outer layer (shield layer)** – a high-density array of miniature SMA protrusions, each with a wide top and a gradually narrowing neck, densely arranged to form the first line of defence. When a stab blade or bullet impacts, the protrusion first receives the impact. Its wide top spreads the concentrated pressure over the cross-section of the protrusion, while the neck undergoes controlled elastic deformation to further buffer the local stress. The primary task of the protrusion is to resist cutting – a blade cannot easily cut into a hard hemispherical surface, nor can it bypass the protrusion to directly cut the underlying mesh.
- **Middle layer (energy-absorbing layer)** – a 2D mesh woven from SMA superelastic wires, pre-stretched to the start of the superelastic plateau. Each mesh node corresponds to one protrusion. When the protrusion is impacted and displaced inward, its neck pulls the four surrounding mesh cells, stretching the mesh laterally into the superelastic plateau – one protrusion drives local energy absorption of the mesh. This is the realisation of “point actuation” in the ballistic protection scenario.
- **Inner layer (cushion layer)** – a biomimetic multi-chamber material similar to the cushion layer in the protective container, attached to the back of the SMA mesh. After the impact force passes through the mesh, this inner layer further dissipates residual energy through viscoelastic deformation and chamber collapse, while also improving wearing comfort by preventing the hard protrusions from pressing directly on the skin.

Why must the three layers be integrally formed? If the protrusions were simply glued onto the mesh, a blade could peel them off or cut into the gaps between protrusion and mesh. But if the protrusions and the mesh are printed from the same SMA material – achieved by additive manufacturing – there are no interfaces, no gaps, no delamination. When a blade cuts, it cuts a single protrusion, but that protrusion is held by the entire mesh – to cut it off, one would have to tear the whole mesh.

Graded response – A weak impact (e.g., low-speed stab) activates only a few protrusions and their surrounding mesh cells, leaving the liner overall soft; a strong impact (e.g., high-speed bullet) activates a much larger area of protrusions and mesh cells, and the energy-absorbing region of the SMA mesh automatically expands with the impact intensity. Compared with hand protection, the ballistic liner deals with high-speed impact with forces orders of magnitude higher, but the physical principle is the same – the SMA wire diameter must be substantially increased, the mesh density increased, and the plateau force preset much higher.

However, the gaps between the modules, although necessary to provide deformation space for lateral expansion, also constitute a potential weakness – a slender stab blade might avoid the top of the protrusions and go straight into the gap. Traditional fish-scale armour uses overlapping to passively cover gaps, but the scales bear forces independently without mechanical coupling.

This paper proposes an improved configuration based on geometric interlocking: the contour of each module is provided with concave-convex interlocking features, and adjacent modules are interlocked with each other to form an “incompletely fixed interlock”. When a blade tries to penetrate the gap, it must push apart the interlocking features of the two adjacent modules – and this “pushing apart” action exactly pulls the roots of both modules, stretching the underlying SMA mesh laterally and absorbing energy. Thus the gap is turned from a weakness into a trigger

for coupled energy absorption. At the same time, “incomplete fixing” ensures that when a module is directly impacted on its top, it can still displace downward independently without being locked by its neighbours. No extra parts are added – the interlocking features are simply part of the module boundary. Shape replaces parts, and geometry realises function – shape is the most streamlined part.

The origin of this design philosophy can be traced back to ancient scale armour – hard scales distribute the impact force and a soft liner absorbs the residual energy. The principle of “hard points protect, soft base absorbs”, spanning thousands of years, finds a new physical realisation in the age of SMA additive manufacturing.

The SMA flexible bulletproof/stab-resistant liner described in this section is a conceptual design. Its actual protective performance must be verified by professional ballistic testing. This paper does not guarantee any protective effect without such verification.

It should be noted that existing research on ballistic materials has extensively covered porous and composite structures using SMA. The distinguishing features of the present concept are: (1) a three-layer integrally formed configuration that eliminates heterogeneous interfaces; (2) the “point actuation” mechanism of the protrusion array that transforms ballistic impact into lateral stretching of the underlying SMA mesh, rather than relying on direct compression or fracture energy absorption of the SMA material itself. The two approaches are fundamentally different in their energy absorption paths.

4. Discussion

4.1 Synergistic value of the two principles

The four case studies demonstrate the synergistic mechanism of Principle 2 and Principle 3 in impact protection. Principle 2 provides a global force decomposition network that transforms any directional impact into axial tension in multiple SMA wires; Principle 3 provides a local force transformation mechanism that converts a concentrated impact into lateral stretching of an SMA mesh. Together, they form a complete protection logic from macro-scale to micro-scale – the web determines “where the force goes”, and the composite cushion determines “how the force is consumed”.

From a system design viewpoint, the synergy realises a depth-wise multi-level protection. The first level is handled by the Principle 3 composite buffer modules, dealing with local high-frequency micro-vibrations and light impacts; the second level is handled by the Principle 2 web of straps, dealing with large-amplitude omnidirectional impacts and providing post-impact resetting. The two levels work independently but share the same physical basis – the superelastic plateau of SMA.

4.2 Cross-paradigm synergy: coupling with Principle 1 (Suture Without Tightening)

Principle 2 and Principle 1 work together in a Parkinson’s wrist tremor intervention device. In that device, the inner ring and middle ring are connected by eight SMA wires arranged in an octa-anchor configuration – exactly the “octa-anchor” topology of Principle 2. However, the functional goal of that device is not impact protection but motion suppression: within a small angular range of wrist tremor (about $\pm 10^\circ$), the SMA suspension wires dissipate tremor energy through the hysteresis of stress-induced martensitic transformation.

This design shows that the applicability of Principle 2 extends far beyond impact protection. Whenever a system requires an “isotropic force response” – whether for absorbing impact or suppressing vibration – the octa-anchor radial web configuration provides a unified mechanical

solution. Principle 2 deals with “how forces are distributed”, and Principle 1 deals with “how a connection accommodates motion”. They can be used independently in different scenarios or together.

4.3 Relationship with graded damping and physical intelligence

The protection mechanisms of Principle 2 and Principle 3 have a natural connection with graded damping (Principle 8). In the web, the magnitude of the impact automatically determines how many SMA wires are stretched and the strain amplitude in each wire. A weak impact stretches only a few wires, which undergo small excursions at the beginning of the plateau, producing a small hysteresis loop and gentle damping; a strong impact stretches many wires, each undergoing a large excursion within the plateau, producing a large hysteresis loop and strong damping.

This “impact strength automatically determines damping strength” mechanism is the natural manifestation of Principle 8 in impact protection. Moreover, the whole process requires no sensors, no controllers, and no power supply, relying entirely on the superelastic plateau of SMA and the biomimetic structural design – which is the core connotation of the principle of physical intelligence.

4.4 Limitations and future directions

The four case studies presented here are still at the conceptual and structural design stage. Quantitative experimental data are lacking on several key parameters: the long-term pre-tension stress relaxation of the SMA straps, the performance degradation of the buffer modules after repeated impacts, and the fatigue life of the web at the corner anchors. For the aerospace landing application, the long-term reliability of the modules in vacuum, extreme temperatures, and high radiation environments must also be verified. The ballistic performance of the stab-resistant liner requires professional testing. The ergonomic adaptation of the cycling and industrial gloves also requires prototype testing and user evaluation. The manufacturing processes for 3D honeycombs and spherical honeycombs – especially high-precision additive manufacturing of SMA – are still at the laboratory stage.

The feasibility of the proposed permanent landing field depends on the energy absorption efficiency data of the SMA buffer modules. The author looks forward to collaboration with aerospace engineering laboratories to experimentally verify the single-impact energy absorption, the degradation after repeated use, and the impact response of the array configuration.

Future work directions include: (1) establishing a force-displacement model of the web under arbitrary directional impacts to optimise the number and placement of anchors; (2) testing the energy absorption efficiency and recovery rate of the composite buffer modules under different impact energies and angles; (3) exploring the layer-by-layer buckling characteristics of SMA cellular structures for landing buffering and their synergistic design with the Principle 3 composite buffer modules; (4) conducting additive manufacturing process validation and impact testing of 3D SMA spherical honeycombs; (5) performing ballistic testing of the stab-resistant liner concept; and (6) fabricating functional prototypes of the cycling and industrial gloves for ergonomic evaluation and impact attenuation testing.

5. Conclusions

This paper has systematically presented two spatial protection principles from the Stiffness-Switching paradigm – the “Octa-Anchor Radial Spatial Web” (Principle 2) and “Point-Actuation Perimeter Absorption” (Principle 3) – including their physical foundations, design methods, and cross-domain applications. Principle 2 uses an isotropic radial pre-tension

network formed by eight corner anchors to decompose omnidirectional impact forces, solving the problem of force distribution. Principle 3 uses discrete point load nodes to drive lateral stretching of an SMA mesh for energy absorption, solving the problem of energy transformation. The synergy of the two principles forms a complete spatial protection system that ranges from macro-scale force decomposition to micro-scale energy dissipation.

Four case studies – a protective container, a spacecraft landing buffer, hand protection (industrial anti-vibration and sports cycling gloves), and an SMA flexible bulletproof/stab-resistant liner – cover precision instrument protection, aerospace engineering, industrial health, sports protection, and personal armour, demonstrating the universality of the two principles.

Building on this protection system, the paper further explores progressive applications of SMA cellular structures. From the layer-by-layer buckling of 2D hexagonal honeycombs, to the isotropic 3D space-filling honeycombs, to the in-plane “force programming” of radial annular composite honeycombs – where for any impact direction there are cell walls working efficiently – the topological evolution reflects the core philosophy of the Stiffness-Switching paradigm: “do not add, but subtract”. Fewer parts, fewer failures.

The Principle 3 SMA biomimetic composite buffer module, starting as a small module on the inner wall of a protective container, expands to industrial anti-vibration gloves, sports cycling gloves, a ballistic liner, and then to a large-area landing field for re-entry capsules – a palm-sized module, when arrayed, can catch an entire spacecraft.

Eight points balance a space. Force at a point drives surrounding energy absorption. The honeycomb collapses layer by layer, absorbing bit by bit. Force programming – I need a force, and it is there. From a single SMA wire to a landing field that catches a re-entry capsule, from a radial web to a radial honeycomb – small structures, big functions. The simplification in spatial protection is always in progress.

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Figure List

- **Fig. 1** Geometric principle of the octa-anchor radial spatial web: eight corner anchors and an isotropic pre-tension network
- **Fig. 2** Physical mechanism of point-actuation perimeter absorption: vertical impact driving lateral stretching of the SMA mesh (including cross-section of the composite buffer module)
- **Fig. 3** Layout of hand protection modules: mechanical load-bearing points for industrial

anti-vibration gloves and sports cycling gloves

- **Fig. 4** Three-layer structure of the SMA flexible bulletproof/stab-resistant liner: trigger layer (point array), energy-absorbing layer (mesh), cushion layer (biomimetic material)

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