Biological considerations in the structural design of smart prosthetics

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***Abstract*—The objective of this paper is to highlight the important characteristics, parameters and obstacles that ought to be taken into consideration when designing the mechanical structure or frame of a robotic anthropomorphic arm, also known as a smart prosthetic arm, with a biological system serving as inspiration. This paper examines the attributes of biological bones which give them their mechanical properties, focusing on the humerus, ulna and radius bones with the notion that a similar approach can be used in the analysis of the biological hand. Through the discussion of available alternative materials and their feasibility, both financially and through application, such as demonstrating self-healing capabilities and also discussing possible solutions; this paper indicates the synergy needed between the fields of engineering, both robotics and mechatronics, and medicine for the advancement of smart prosthetics.**

Keywords-Biological bone; force-to-weight ratio; smart prosthetics.

I. Introduction

The human body is arguably the world's greatest marvel and inspiration in numerous fields including engineering. Throughout the ages nature has been a source of inspiration in terms of inventions and problem solving. One field that has always taken its inspiration from nature is that of Robotics. We have entered the age where robotics has gone well beyond its industrial beginnings and into areas such as mining, underwater exploration and even space exploration. Robots are also finding their way into our everyday lives, being used in the field of medicine for diagnosis and rehabilitation purposes, prosthetics and even as surgeons [1].

Numerous research has been done and is still currently underway in the design of smart prosthetics with the focus being on the control system though overlooking the frame or foundation of the prosthetic which is equivalent to the bone of its biological inspiration. Prosthetic legs have found their way into the 21st century, in terms of their design and control, though prosthetic arms still lag decades [2] behind with purely mechanical prosthetics such as hooks being the most readily available arm prosthetic when taking into consideration functionality and expense.

Taking our cue from nature, we are able to model and design systems that maximise the functional advantages of nature without completely mimicking nature, resulting in less technological complexity. The objective is to simulate the behaviour or function of the biological system of the bone within the robotic systems structural/mechanical frame. This paper will be focused on the upper extremity smart prosthetics, studying the biological bone of the humerus, radius and ulna.

Robotic prosthetics face a number of challenges, not only in their design but also when being integrated with the human body; refer to Figure 1 [3], [4]. One of the reasons why a majority of patients cease to use their prosthetics after a year or two of acquiring said prosthetic is because of its lack of comfort [5]. Besides the challenges of control, robotic prosthetics, sometimes referred to as smart prosthetics, need to be comfortable enough to allow use by those who need them on a regular basis.

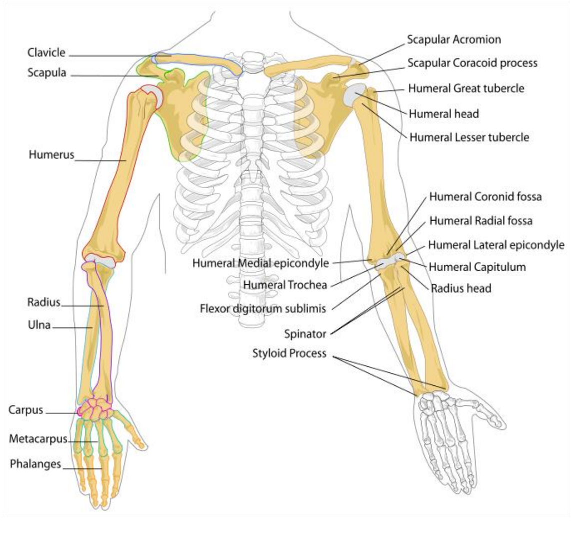

Figure 1. Upper extremity bone

The regular use requires smart prosthetics to meet the following criteria:

- Be light weight
- Have a force-to-weight ratio similar to their organic counterparts
- Be energy efficient or to not even rely on an external energy source

One way in which the prosthetics criteria mentioned above can be achieved is by redesigning the prosthetic structure (mechanical frame) which can be seen as the equivalent to the bone in its biological counterpart. The question is how do we mimic the function and

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characteristics of the biological bone in the designing of smart prosthetics or possibly even to serve as replacements, to some degree, to their biological counterparts?

The sections to follow will discuss the biological bone, exploring its microscopic structure, characteristics and examining its mechanical properties. Current smart prosthetics will also be briefly discussed, followed by the exploration of alternative solutions and mechanical possibilities, thus leading up to the conclusion.

II. BIOLOGICAL BONE

The focus of this paper will be on biological bones' mechanical function and characteristics and focusing on the elements that would enhance the criteria for regular use of the smart prosthetic.

A. Characteristics

Bones serve three fundamental purposes [6]:

- A synthetic function;
- A metabolic function; and
- A mechanical function.

Bone is made up of a number of layers, each contributing to a particular aspect of its mechanical properties. Osseous tissue, a relatively lightweight but hard composite material mostly formed of calcium phosphate, is the bones primary tissue. Osseous tissue gives bones their rigidity and consists of both living and dead cells embedded in its mineralized organic matrix. Bone is not uniformly solid; it has spaces between its hard elements which contribute to its light weight.

Bones consist of two fundamental layers, the cortical bone and the trabecular bone. The cortical (compact) bone is the hard outer layer of the bone which gives the bone its white, smooth and solid appearance. It is the dense tissue usually found on the bone surface which has minimal spaces and accounts for roughly 80% of the total bone mass of the healthy human adult skeleton. The cortical bone is organised in concentric lamellae called osteons; refer to Figure 2 [7].

The trabecular bone forms the interior of the bone. It accounts for the remaining 20% of the total bone mass in a healthy human adult skeleton due to its network of rod and plate like elements resulting in a number of spaces within the bone. Refer to Figure 3 [7].

The trabecular bone is organised in trabecules whose orientation is dependent on the direction of the physiological load and also on the external loads' anatomical site, making it rather variable. The trabeculae rearrange themselves in the event of the alteration in strain subjected to the cancellous (spongy part of the trabecular bone).

The mechanical strength of bones is due to the bone matrix which forms the majority of the bone. Bone is formed by the entrapment of cells, by osteoblasts, during the hardening of the bone matrix. The bone matrix is composed of organic and mineral (inorganic) phases, though a liquid is also present. The organic phase of the bone matrix is mainly composed of collagen fibres which gives bones their degree of elasticity. The mineral (inorganic) phase of the bone matrix is composed of carbonated hydroxyapatite ($Ca_{10} (PO_4)_6OH_2$) with lower crystallinity.

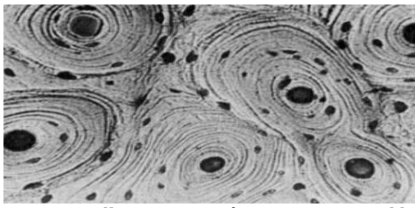

Figure 2. Lamellar structure of osteons in cortical bone

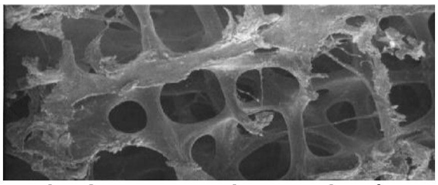

Figure 3. Trabecular structures in the L1 vertebra of a 24 year old

B. Mechanical Properties

Biological bones do not have completely constant mechanical properties, but rather demonstrate slightly varying mechanical structures dependant on the stress and strain to which they are subjected. The bones mechanical properties is the result of the numerous structures of the cortical and trabecular bones in relation to changing loading conditions; and also vary according to age, anatomical site, liquid content and other such parameters.

As can be deduced from Table 1, the common attributes of the human bone in all the above noted ages is that the human bone is most resilient to compression and bending, indicating its resilience to loads it is subjected to under everyday normal use [7]. The principle of biological bones rigidity and mechanical properties as a function of applied load and loading position and direction is also subsequently evident. Bones in different parts of the body have different mechanical properties, with the bone area playing a significant role in said properties, just as cross-sectional area and surface area affect the stress and strain parameters in any mechanical structures.

TABLE I. ULTIMATE STRENGTH (MPA) AND ULTIMATE STRAIN (%) OF CORTICAL BONE FROM THE HUMAN FEMUR AS A FUNCTION OF AGE

	Age (years)						
Property	10-20	20-30	30-40	40-50	50-60	60-70	70-80
Ultimate strength (MPa)							
Tension	114	123	120	112	93	86	86
Compression	-	167	167	161	155	145	-
Bending	151	173	173	162	154	139	139
Torsion	-	57	57	52	52	49	49
Ultimate strain (%)							

Tension	1.5	1.4	1.4	1.3	1.3	1.3	1.3
Compression	-	1.9	1.8	1.8	1.8	1.8	-
Torsion	-	2.8	2.8	2.5	2.5	2.7	2.7

Table 2 indicates the mechanical properties of leg and arm bones with loads applied longitudinally [8]. As indicated in Table 2, leg bones have higher compressive strengths due to the force they experience during walking, running or doing similar activities.

TABLE II PROPERTIES OF BONE (ADAPTATION)

Tissue	Direction of test	Modulus of Elasticity (GPa)	Tensile Strength (MPa)	Compressive strength (MPa)
		Leg bone		
Femur	Longitudinal	17.2	121	167
Tibia	Longitudinal	18.1	140	159
Fibula	Longitudinal	18.6	146	123
		Arm bone		
Humerus	Longitudinal	17.2	130	132
Radius	Longitudinal	18.6	149	114
Ulna	Longitudinal	18.0	148	117

However, arm bones, more appropriately the radius and ulna, have higher tensile strength as compared to their compressive strength due to the variety of tasks the arm needs to perform; such tasks include numerous push and pull variations meaning the arm needs a good balance of both compressive and tensile strength for optimal functionality.

As with any other material, the type, rate and direction of loading are important aspects that influence the manner in which the bone will react to the load in question. The principal stress and strains under different loading conditions of the bone are some of the aspects that should be quantified in the design of optimal mechanical structures for smart prosthetics taking their inspiration from nature.

Figure 4 illustrates how the Young's modulus (E), also known as the Modulus of Elasticity, the yield strength and the ultimate compressive strengths increase in near proportionality to the rate of loading [8].

The point of strain failure and the fracture toughness of the bone reaching its maximum followed by its decrease indicate the existence of a critical loading rate, as experienced in any other mechanical structure.

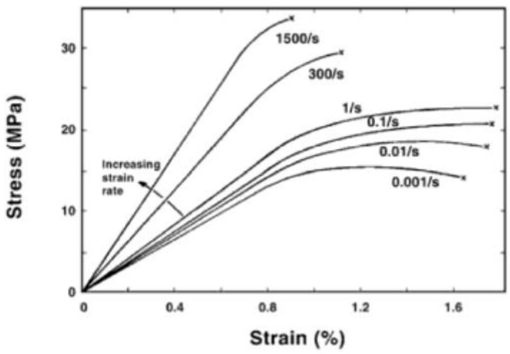

Figure 4. Stress as a function of strain, and strain rate for human bone

The mechanical properties of the cortical bone vary in response to the direction in which a load is applied; this makes it an anisotropic material, refer to Figure 5 [7]. The cortical bone is also classified as an orthotropic material, which is a classification of anisotropic materials characterised by three Young's moduli values (E_x, E_y, E_z), three Shear moduli values (G_{xy}, G_{xz}, G_{yz}) and six Poisson's ratios (ν_{xy}, ν_{xz}, ν_{yz}, ν_{yx}, ν_{zx}, ν_{zy}) in relation to the three axial directions (x, y, z) to which load is applied.

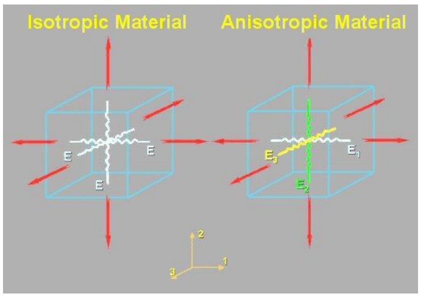

Figure 5. Comparison of the mechanical behaviour of isotropic and anisotropic materials

The mechanical properties of the trabecular bone are more complex in characterization as compared to the cortical bone. This is due to the varying mechanical properties of the trabecular bone undertakes as a response to varying applied loads and at varying directions of load application. The mechanical properties of single trabeculae define the mechanical properties of the trabecular bone as a whole. The Young's modulus of the trabecular bone is highly dependent on its bone density as shown below in Figure 6 [7].

It is approximated that the ultimate tensile strength of the upper extremity bones in descending order are as follows, the radius (15.2 kg/mm^2), the ulna (15.1 kg/mm^2) and the humerus (12.5 kg/mm^2). Biological bones demonstrate incredible mechanical properties especially in relation to their weight and dimensions.

Some of the characteristics biological bones demonstrate include the following:

- Load absorption
- Healing abilities
- Ability to alter microscopic structure to better adapt to load changes, both force and direction

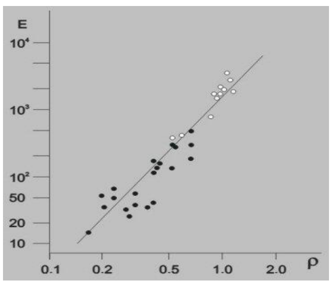

Figure 6. Young's modulus of trabecular bone as a function of density of bone. Bone density "ρ" is expressed in g/cm^3 and Young's modulus "E" in MPa

The improvement of smart prosthetics would also rely on being able to mimic the three biological bone characteristics as above mentioned.

III. Current Smart Hand Prosthetics

There are now a number of smart upper extremity prosthetics available, some commercial and others to undergo clinical trials; such prosthetics include Otto Bocks Michelangelo hand, Touch Bionics iLimb, the Deka arm, the Fluid Hand, the Bebionic Hand and many others. What these arms have in common is their use of metal or metal composites and/or polymers in the construction of their arm and/or hand structures.

Even with some of the advantages metals and polymers possess, they have certain disadvantages that, to some or other extent, influence the overall performance and effectiveness of the prosthetics. Another factor of consideration is the fact that prosthetics are designed to be worn on a regular basis, meaning a good degree of biocompatibility should exist between the smart prosthetic and the existing biological structure.

Table 3 attests to the fact that a large portion of patients do not use prosthetics, almost 50% [5]. This can of course also be attributed to a number of other factors aside from comfort; such factors may include patient accessibility to certain medical facilities, finances and more so to which degree the prosthetic would actually enhance mobility and freedom. However, leg prosthetics are found to be used more frequently as compared to arm prosthetics [5]. This can also be attributed to factors such as a higher level of comfort, compared with arm prosthetics and more so the technological advancements leg prosthetics have had, thus allowing for increased mobility and freedom.

The focus of smart prosthetics goes beyond just the control of the prosthetics, but also encompasses the design of prosthetics that would be comfortable, light weight enough for a patient to be willing to use on a regular basis and able to function in a number of different environments.

The majority, if not all, of the available prosthetic arms have a limitation in terms of the environments in which they can be used. The design of the mechanical structure to be used as the frame in smart prosthetics should, like the rest of the arm, take its cue from its biological counterpart. The question thus becomes, what materials do we use for the mechanical structure of the smart prosthetic arm? Are alternative materials financially viable?

IV. Mechanical Possibilities

As can be deduced from earlier discussions, it is both the bone dimensions and its material composition (including its microscopic layout) that give biological bones their phenomenal force-to-weight ratio. Motion of any biological being is caused by muscle action. In the case of the arms (and the legs) the majority of those muscles are connected to the bones through tendons.

TABLE III. CLINICAL CHARACTERISTICS OF PERSONS WITH UPPER-LIMB (N = 107) AMPUTATION AND PROSTHETICS USE (ADAPTATION)

Prosthesis Use (%)	
Yes*	56.1
No*	43.9
If Yes: Hours per Day, Mean ± Standard deviation (range)	10.67 ± 5.00 (1–24)
If Yes: Days per Month, Mean ± Standard deviation (range)	24.45 ± 8.5 (1–31)
Location of Amputation: Upper Limb (%)	
Fingers	4.7
Partial Hand	14.0
Wrist Disarticulation	5.6
Transradial	30.8
Elbow Disarticulation	1.9

The curvature of the radius bone, in conjunction with the ulna, allows for more stability during the rotation of the wrist and a wider degree of freedom both at the wrist and the elbow, with the radius bone becoming thicker in dimension as it nears the wrist.

TABLE IV. DIMENSIONS OF MALE AND FEMALE ABORIGINAL HUMERI (MM)

	n	$\overline{X}$	**Standard Deviation**
Left humerus maximum length			
Male	195	323.9	16.22
Female	147	303.5	16.05
Left humerus maximum mid-shaft breadth			
Male	95	19.8	1.72
Female	101	17.1	1.60
Left humerus minimum mid-shaft breadth			
Male	92	15.6	1.49
Female	73	12.8	1.29
Left humerus vertical head diameter			
Male	89	41.6	2.36
Female	88	36.5	2.12
Left humerus distal articular surface breadth			
Male	59	42.0	2.33
Female	73	37.3	2.21

The physical dimensions of any bone in the human skeleton rely on parameters such as gender, age, DNA and health aspects. Men possess slightly longer and wider bones as compared to women; this is again another factor to be considered in the design of smart prosthetics as this will affect the force-to-weight ratio of the prosthetics as the dimensions alter; refer to Table 4 [9] and Table 5 [9]. Thus care should also be taken when designing generic prosthetics for males and females as heavier prosthetics would function better on males compared to females due to the bigger bone structure males possess.

TABLE V. DIMENSIONS OF MALE AND FEMALE ABORIGINAL RADIUS AND ULNA (MM)

	n	$\overline{X}$	Standard Deviation
Left radius maximum length			
Male	134	252.7	13.19
Female	95	231.5	13.9
Left ulna maximum length			
Male	127	269.9	12.47
Female	82	247.9	14.22

It can be quantified that the principal stress and strain can be found nearer to the joints, which experience some of the greatest loading in the human body. The objective thus becomes to design a 'mechanical bone' that will slightly taper off from the beginning of the bone to the middle and again slightly uniformly increase in dimension from the middle to the end of the bone, mimicking the dimensions of its biological counterpart. This dimensional design of the mechanical frame would be similar to two trombones cut in the middle and joined, though with a smaller degree of tapering.

There exist a number of materials that could be used in the design of the mechanical frame of smart prosthetics, with the consideration of the required force-to-weight ratio at least equivalent to that of humans, being roughly 4:1. Table 6 lists possible materials along with their mechanical properties [10].

As can be deduced from Table 6, the most viable material that could be used in the design and manufacture of the mechanical is alumina-zirconia. Research has found that the inclusion of hydroxyapatite within the alumina-zirconia, at approximately 3% wt [11], betters the materials biocompatibility and allows for functionally closely related to its biological counterpart; this is because calcium hydroxyapatite forms one of the materials present in the inorganic matrix of the biological bone.

TABLE VI. POSSIBLE MECHANICAL FRAME MATERIALS (#ASTM GRADE 1, *ALLOY 1100 – STRAIN HARDENED, & CARBON (PAN PRECURSOR) STANDARD MODULUS

Material	Properties			
	Young's Modulus (GPa)	Tensile Strength (MPa)	Yield Strength (MPa)	Flexural Strength (MPa)
Titanium#	104	240	170	-
Aluminium*	70	124	117	-
Carbon fiber& (long)	230	3.8	-	-
Alumina-Zirconia	330	1.4	-	550

The next obstacle would be to find a way of enabling the mechanical frame to heal itself as attributed by its biological counterpart. One way to achieve this ambitious goal would be to coat the alumina-zirconia mechanical frame with a self-healing material, thus allowing the frame to heal cracks of certain dimensions and, to some extent, recover from normal use loading. Self-healing materials are essentially polymer coatings containing catalyst pieces scattered throughout. They have networks of micro-channels which carry liquid healing agents a distance further within their 'host material'. When the coating cracks and continues further within the 'host material', it eventually reaches the underlying micro-channels subsequently releasing the healing agent which mixes with the catalyst forming a polymer hence filling (or healing) the crack [12].

Taking the intelligence to be integrated onto the mechanical frame, to allow for actual movement and control of the arm, the structure should also be able to aid in minimising induced vibrations with the subsequent incorporation of motors, sensors and similar devices. The human body, more specifically the skeletal system, is able to handle vibrations better as compared to metallic structures due to the presence of pores within the trabecular bones. Alumina-zirconia being a ceramic allows it to demonstrate the hard, smooth outer shell of the mechanical frame, which is equivalent to the cortical bone. Sintering of alumina-zirconia with hydroxyapatite allows for the formation of larger pores [13] allowing it to react or handle vibrations and normal loading exceptionally well.

The large pores created during the formation of alumina-zirconia through the above mentioned sintering process allows the material to demonstrate similar light weight but strong characteristics of a biological bone; coupled with the necessary, technologically advanced, intelligence to allow function and control of the smart prosthetic could see force-to-weight ratios rather similar to that of human beings and better than any other available smart prosthetic.

Classical materials such as aluminium and titanium could be used as they are considerably more financial viable in terms of availability and machining. However, these metals do not possess the biological-like characteristics that the alumina-zirconia, with the incorporation of hydroxyapatite, demonstrates; not to mention the mechanical properties. Carbon fibre could also be an alternative material as it demonstrates exceptional mechanical properties in relation to its weight, though its advantages are outmatched by the financial viability of aluminium and titanium, as well as the level of biocompatibility of aluminium, titanium and alumina-zirconia; refer to Table 7. Synthetic hydroxyapatite is not an option alone as it is neither financially viable to manufacture, nor does it possess mechanical properties good enough to even match those of biological bones.

TABLE VII. APPROXIMATE MATERIAL PRICES (08 MARCH 2010 – 04 MARCH 2011)

Material	Price (US$ / kg)
(Ferro) Titanium	8.5
Aluminium (LME Settlement)	2.60
Carbon Fiber (BS 1701Coarse)	18

Alumina	3.5
Zirconia	4.1

Being able to mimic the characteristics and force-to-weight ratios of biological bones will result in lighter smart prosthetics as a whole. Alumina-zirconia sintered with hydroxyapatite is but one of the material combinations that result in a structure similar to that of its biological inspiration. However, this material does have its limitations, one of which being that it is rather brittle.

As discussed earlier in this paper, the radius and ulna human bones possess higher tensile strength as compared to their compressive strength. However, the humerus bone possess higher compressive strength compared to its tensile strength, this means that the sintered alumina-zirconia with a layer of self healing polymer would be able to effectively mimic the functionality of the biological humerus bone. Taking the same approach however, would mean a thicker self healing polymer layer would be required for the radius and ulna bones, thus providing a higher tensile strength for that portion of the mechanical frames as well as a higher degree of self healing capability, especially seeing (from Table 3) that the largest location of upper extremity amputation is transradial.

V. CONCLUSION

As discussed throughout this paper, the biological bones mechanical properties are of great interest when designing prosthetics, more so smart prosthetics. The mechanical structure alone is of course not enough to create a smart prosthetic. Intelligence such as motors for movement or sensors which allows the smart prosthetic to interact with its immediate environment still needs to be integrated. Taking into consideration the intelligence/technology which is to be incorporated around the mechanical structure of any smart prosthetic, a more rigid and relatively elastic material would be required. These requirements introduce the possibility of incorporating titanium [14] within the alumina-zirconia material, even as a coating of sort. The introduction of titanium would be to extend the materials yield point thus resulting in a mechanical structure which would be more resistant to fatigue and ultimately, fracture.

The incorporation of titanium within the alumina-zirconia results in a mechanical structure which could be seen as somewhat of an improvement on the biological bone, in terms of mechanical properties. This once again emphasises the mimicking of **function** when formulating or designing biologically inspired solutions, rather than only mimicking the structure in question, thus allowing for simpler models, designs and technological solutions.

Another important factor in the development of comfortable and light weight prosthetics would be the possible exclusion of the prosthetics harness. The exclusion of the harness would mean that the smart prosthetic would have to be directly fixed to its biological host.

As engineering and medicine disciplines progress and inter-phase in the area of smart prosthetics and venture into neurologically controlled smart prosthetics, more important is the mastering of the design of the smart prosthetic mechanical frame. The ultimate goal of this work is to strive to fully integrate the smart prosthetic to its biological host, allowing for a true replacement of the amputated biological limb. The full integration of the smart prosthetic would also be possible with the design and development of light-weight, fully biocompatible [15] mechanical frames that may be used to substitute for the missing ligament bone(s). This ambitious goal can only be achieved through the advancement of material science, bone grafting [16] techniques, the use of osteoconductive materials and stronger multidisciplinary relations, such as those between the engineering and medical fields.

Engineering and medicine have made great strides over the past decades and still have a journey ahead as academia and industry strive to better systems and designs with the aid of technological solutions. A holistic approach should be taken in the design, more so for biological inspired systems. This paper has aimed to demonstrate the type of holistic approach that may be used in the design of mechanical frames for smart prosthetics with the human humerus, radius and ulna bones serving as inspiration.

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