Towards a Anthropomorphism Theory for Human-like Machines Based on Systems Science

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Abstract: Human-like machines are based on a purely intuitive anthropomorphic approach. In this framework, a theory of anthropomorphism could help for the analysis of the consequences made by the designer in his endeavor to mimic the human physiology. The paper aims to highlight the possibilities of the system theory in its application to a rigorous definition of anthropomorphism.

Key-Words: Anthropomorphism, Human-like machines, Systems theory

1 Introduction

In a general manner, anthropomorphism is the tendency to attribute human characteristics to objects or non-human organisms with a view to helping rationalize their actions. Social robots can use this natural human tendency for increasing their functional and behavioral characteristics. Near this "negative" sense of anthropomorphism, consequence of our disagreement about the uniqueness of human beings, a "positive" sense of anthropomorphism can be considered : anthropomorphism as the act of giving a human form to something. Humanoid robots are a direct consequence of this creative approach of anthropomorphism. Design meaning about "anthropomorphism form" can help us to specify the humanoid robot anthropomorphism. In a recent study, the Carnegie Mellon university school of design [1] has proposed to distinguish four kinds of anthropomorphic form inspired from a rereading of Buchanan's four orders of design : things, symbols, action and systems or thought. Carnegie Mellon' authors consider successively :

- *A structural anthropomorphic form*, imitating the "construction and operation of the human body with a focus on its materiality", as provided by a jointed small-scale pose-able artists model;
- *A gestural anthropomorphic form*, imitating the "ways people communicate with and through the human body with a focus on human behavior", as provided by some computer screen mimicking a human-like behavior when an incorrect password is entered (window shaking, for example, on the Mac OS 10.2 login screen);
- *An anthropomorphic form of character*, imitating "the traits, roles or functions of people", as performed by certain perfume or beauty treatment bottles emphasizing some male or female character;
- *An aware anthropomorphic form*, imitating "the human capacity for thought, intentionality or inquiry", as provided by number of science-fiction robotized heroes.

This typology clearly exhibits the very large spectrum of the word 'form' in the definition of the 'anthropomorphic form' expression, from structural considerations to complex behavioral considerations. In some sense, active humanoid robots are supposed to cover all this anthropomorphic form spectrum : human appearance, human-like behavior and even theory of mind. The humanoid robot would be the highest level of anthropomorphism but also its highest complexity level. That is why we think that systems theory could be particularly helpful for the development of an anthropomorphism theory adapted to human-like machines. The paper is organized as follows : in a first part, we recall the importance of the systemic approach in physiology; in a second part, we will propose to reconsider a mathematical definition of systems to apply it to the definition of anthropomorphism; we will then introduce a fundamental distinction between local and global anthropomorphism and we will apply this approach to the skeletal system anthropomorphism. In a last section, we will emphasize the limitation of any local anthropomorphism and we will try to deduce an original analysis about the actual difficulties of humanoid robots to mimic the complete musculoskeletal system.

2 The Systemic Approach in Physiology

Actual physiology is based on the concept of homeostasis considered as a fundamental equilibrium general principle of the human body. Homeostasis is directly inspired by Wiener's cybernetic theory : through specific sensor data homeostasis imposes a feedback to regulate fundamental human body parameters like temperature. But the influence of cybernetic theory to human physiology can also be seen in the definition of physiological systems. Physiological treatises generally distinguish eleven fundamental systems defining a function to be performed by related organs :

- The ***skeletal system*** supporting the body and allowing its mobility by means of skeletal muscles ;
- The ***muscular system***, generally limited to skeletal muscles, making possible the skeleton mobility and giving in consequence the possibility for the individual to feed and to escape from danger ;
- The ***nervous system*** controlling and coordinating the responses of the body face to a changing environment ;
- The ***circulatory system*** serving as a "transportation system" to transfer oxygen, fuel, nutrients, waste products, immune cells, and hormones from one part of the body to another ;
- The ***gastrointestinal system*** converting food into nutritional molecules for distribution by the circulation to all tissues of the body, and excreting the unused residue ;
- The ***respiratory system*** bringing to the body oxygen from air and excreting carbon dioxide and water back into air ;
- The ***urinary system*** removing water from the blood to produce urine, which carries a variety of waste molecules and excess ions out of the body ;
- The ***immune system*** providing a mechanism for the body to distinguish its own cells and tissues from alien cells and substances and to neutralize or destroy the latter ;
- The ***endocrine system*** producing specific hormones which serve as signals from one body system to another ;
- The ***integumentary system*** providing containment and protection for other organs, and serving as a major sensory interface with the outside world ;
- The ***reproductive system*** aimed to the spece conservation.

It is seldom remarked that the definition of these systems is in full accordance with the mathematical definition of a system as a set of elements jointed by imposed relationships. In some sense, the study of each physiological system consists in highlighting specific relationships putting in work the corresponding function by means of organs. We think that such a global systemic structure of the body can serve as an outline for an human-like anthropomorphic structure aimed to mimic the functions of the human body.

However the question arises : which physiological systems a human-like anthropomorphic structure must privilege ? Because every physiological system is dedicated to a specific function, it can be understood at a phenomenological level and its elements can be modeled at a macroscopic level in ignoring the details of the microscopic level. If the main goal of our anthropomorphic approach consists in designing a human-like machine, a comparison can be established between considered physiological systems and autonomous machine functions. In a general manner, it can be considered that an autonomous machine is characterized by four main functions : a ***mobility function*** necessitating an adapted mechanical structure and associated actuators, a ***sensitive function*** performed by both proprioceptive and exteroceptive sensors, a – high and low level – ***control function*** and a ***supply function*** realized by embedded batteries. Table 1 draws a parallel between the eleven considered physiological systems and these four main autonomous machine functions. Let us note that the reproductive system does is not present in this table : it is by nature the life specificity in comparison with machines.

physiological systems	***corresponding machine function***
Skeletal system *Muscular system*	mobility
Nervous system *Immune system* *Endocrine system*	control
Integumentary system *- with special senses* *(vision, hearing, taste* *an d smell) -*	protection and sensing
Circulatory system *Gastrointestinal system* *Respiratory system* *Urinary system*	supply

Table 1. Correspondence between physiological systems and major autonomous machines major functions.

Furthermore, the considered presentation order for machine functions can also be considered as a hierarchical order : mimicking the human mobility appears to be the most important part of a human-like machine, and more accurately mimicking the skeleton kinematic structure before its actuation structure. For this reason, the skeletal system seems to us the first one to mimic, as actual humanoid robots do it in associating a kinematic human-like structure with non-biomimetic electrical actuators.

However if such a hierarchical analysis has an undeniable intuitive value, it can be asked how to give a rigorous status to the adopted model of each considered system. For example, actual kinematic structures of humanoid robots are generally not justified by a preliminary anthropomorphic analysis. We think that the application of mathematical theory of systems can help for giving a rigorous framework to human-like machines anthropomorphism.

3 Systemic Approach of Anthropomorphism

In the sixties, Mesarovic developed a mathematical theory of anthropomorphism which seems to us very relevant for developing a rigorous approach of anthropomorphism. Mesarovic's main idea consists in defining "the notion of a general system as a relation on abstract sets" (page 203) [2] from where it deduces a "mathematical theory of general systems". One major definition of this theory is the following one. Let us consider a family of sets X_1 ,…, X_n , whose as said by Mesarovic "elements are the system terms" and let us define the Cartesian product $X = X_1 \times X_2 \times .. \times X_n$. The explicit definition of a general system is given (page 371) [3] :

' A general system is a subset of the Cartesian product X : $X_S \subset X$ ' (1)

This equation can be applied to any type of system, real ones or abstract ones. In particular in the case of the considered physiological systems, it is possible thanks to this approach to propose a mathematical writing of the considered system as soon as its components have been identified as elements of identified sets. Equation (1) finally expresses the system relationships between the system components as a mathematical relation. Let us consider, for example, the skeletal system. As a system, it is clearly a set of bones joined by physiological joints independently of the knowledge of muscles moving these joints. Let us call *BONE* the set of bones constituting the human skeleton and let us call *JOINT* the set of physiological joints as defined by human joint physiology. According to equation (1) definition, and since any physiological joint joins two bones, the skeletal system noted *SKEL* can be defined by :

$$SKEL \subset BONE \times BONE \times JOINT \quad (2)$$

For example, the triplet (scapula, humerus, glenohumeral joint) is an element of SKEL. The complete specification of *SKEL* necessitates to define all triplets belonging to it.

Defined in this way, the skeletal system cannot be a study object : it is a real system to which it is necessary to associate an abstract or model system. We will present further a model-system of the human skeletal system. In a general manner, it is natural to derive a model-system X_S^M of a real system X_S from the specification of models of all sets constituting the real system. Let us note X_i^M the model-sets of the X_i real sets. The model-system is consequently defined as follows :

$$X_S^M \subset X_1^M \times X_2^M \times .. \times X_n^M \quad (3)$$

The determination of the model-system corresponds to a modeling process specific to the considered system and that can de defined as a mapping from X_S to X_S^M as follows :

$$\begin{array}{ccc} X_S & \rightarrow & X_S^M \\ \subset X_1 \times .. \times X_n & & \subset X_1^M \times .. \times X_n^M \\ x = (x_{S_1}, ..., x_{S_n}) & \rightarrow & x^M = (x_{S_1}^M, ..., x_{S_n}^M) \end{array} \quad (4)$$

Without mentioning at our knowledge the fundamental Mesarovic's work, polish theorists in biomechanics [4-5] have applied this mathematical approach of the system modeling as transformation of sets to an original and powerful definition of the anthropomorphism that we propose to adopt in this paper: let us consider that X_S represents a physiological system as considered earlier and that X_S^M represents its model, the mapping defined by equation (4) will be called in this case ***anthropomorphism of the physiological system*** X_S . It corresponds to a "local anthropomorphism" by opposition with a "global anthropomorphism" corresponding to the ideal situation in which X_S would represent the whole human body. Let us illustrate this approach in the particular case of the skeletal system.

Anthropomorphism of the skeletal system consists so to determine the modeling of the human skeletal system in the form of a system :

$$SKEL^M \subset BONE^M \times BONE^M \times JOINT^M \quad (5)$$

where $BONE^M$ and $JOINT^M$ are the model-sets of respectively *BONE* and *JOINT*.

We have recently discussed in the framework of a paper dedicated to the estimation of the human shoulder complex [6] the modeling question of bones and physiological joints. Extending historical Dempster's notation, we have proposed to kinematically represent any skeletal bone like a mechanical link reduced to the straight-line joining proximal and distal joint centers in the case of a 'single link' (the femoral link, for example) or in the form of a hachured polygon joining the joint centers in the case of a 'complex link' i.e. with more than two joints (the scapula link, for example). It is important to note that if the set *BONE* includes all the skeleton bones, some elements of the set $BONE^M$ can be defined as bringing together several bones, in accordance with kinematic assumptions made. For example, due its kinematic complexity and /or limited movements, it can be decided to bring together several carpal – respectively tarsal – bones with almost immobile metacarpals 2 and 3 – respectively metatarsals – as made further in Fig. 3. Furthermore, we have shown the relevance to approximate each synovial joint by a classic lower mechanical pair as presented in Table 2. In consequence, we can write in extension the $JOINT^M$ set as follows :

$$JOINT^M = \{spherical\ jt, planar\ jt, universal\ jt, revolute\ jt\}$$

synovial joint	type	ball-and-socket joint	flat joint	condyl or ellipsoidal joint	saddle-shaped joint	trochoid or pivot joint	hinge joint
	d.o.f	3	3	2	2	1	1
corresponding	mech. joint & symb.	spherical joint	planar joint	universal joint		revolute joint (or)	

Table 2. Correspondence table between physiological joints and mechanical joints (see [6] for more details).

In the case of the real system as in the case of the model system, any element in the form (bn_1, bn_2, jt) can be understood according to the following relationship : 'the bone bn_2 is mobile in reference to the bone bn_1 by means of the joint jt'. Although our relational system is not strictly speaking a binary system, we can propose to represent it like the binary system $BONE \times BONE$ – or $BONE^M \times BONE^M$ – using the associated joint data as an additive information of the arrow from one node to the next one, as illustrated in Fig. 2 (generally the link orientation is from proximal bone to distal one).

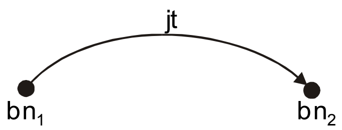


Fig.2. Principle sagittal representation of the skeletal system in which the nodes are the bones and the links are the joints with their associated name – case of the real system – or associated type – case of the model system

We will use further this sagittal representation mode for the study of the musculoskeletal system. In the case of the skeletal system a more suggestive representation can be considered directly inspired from mechanisms representation and which can be understood as the symmetrical representation mode of the previous one : each link corresponds to a bone and each node to a joint. According to this approach, Fig. 3 gives a possible representation of the human skeletal system in which only synovial – mobile – joints have been considered and following anatomical assumptions to be presented in a fore coming paper. We see so how the theory of relational systems applied to anthropomorphism can lead to a rigorous schematic representation of the skeletal system. Let us see now how it can help to measure it.

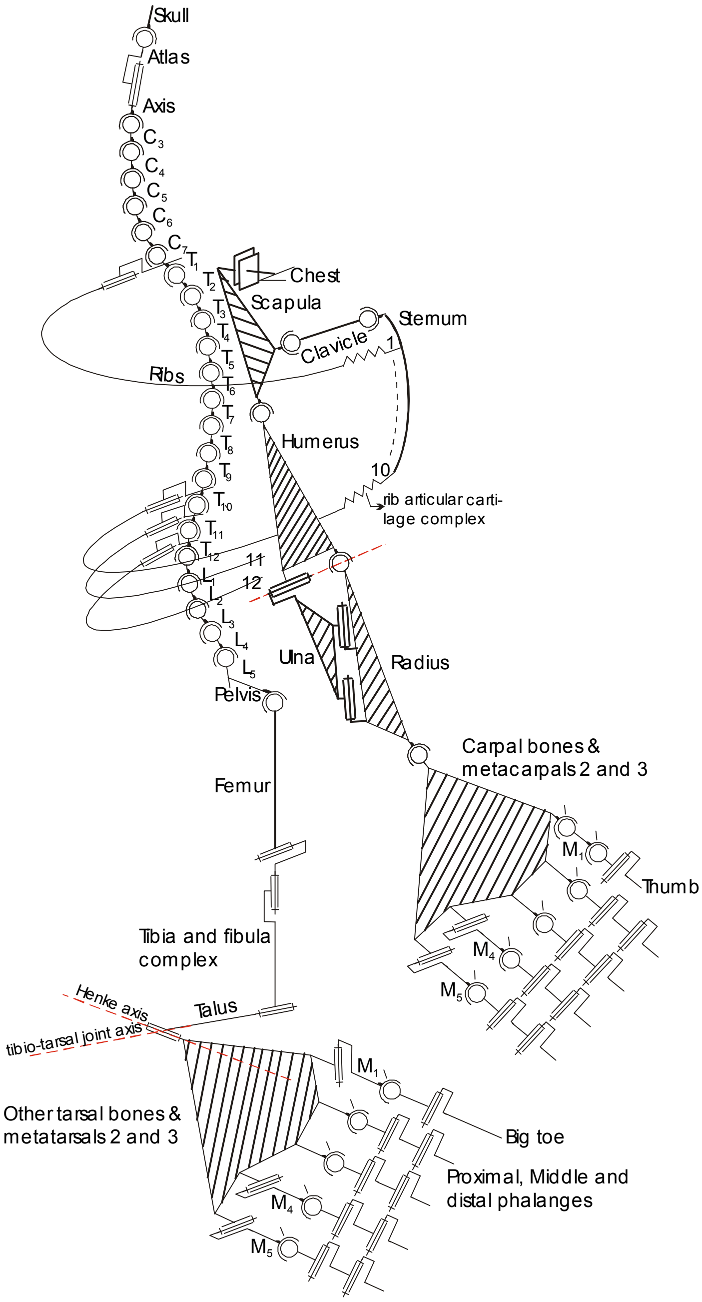


Fig.3. Representation of the skeletal system model in which bones are represented by links and joints by kinematic symbols.

3 Measure of the Anthropomorphism

The anthropomorphism has been defined as a qualitative process designing an abstract model from a real one. It is however possible to associate to this process a measure based on the set nature of considered systems. In their approach of anthropomorphism, Morecki and his team [5] has proposed the following anthropomorphism criterion μ :

$$\mu = Power(X_S^M)/Power(X_S) \qquad (6)$$

where the function *Power* designates the number of elements of the corresponding set. This set-power ratio represents, in some sense, the complexity loose induced by the modeling process. For example, in the case of the skeletal system, as earlier defined, the power of the actual system is equal to the number of all identifiable diarthroses and the one of the model system to the number of all modelized diarthroses. In doing like that all diarthroses are supposed to get the same importance independently of their effective mobility. More generally, if this anthropomorphism criterion appears to get a general and true mathematical validity, its physical value can be poor. For this reason, we prefer to redefine it as a power ratio between the developed model and a reference model defined as the most accurate model of the actual system in a given physical context :

$$\mu' = Power(X_S^M)/Power(X_S^{M-ref}) \quad (7)$$

For example, in the case of the skeletal system, it can be assumed that weak mobility diarthroses have not to be considered in the reference model. This assumption will lead in our model to consider some sets of bones – in particular in the hand or the foot – as single links, as illustrated in Fig. 3 kinematic structure which will serve us as a reference model for the human skeleton.

However, even after this redefinition, the considered anthropomorphism measurement can be always too mathematical and too global also. It can be asked if more specific criteria could be highlighted in order to compare the actual model and the reference model. The look for these criteria depends on the system specificity. In the case of the skeletal system, one such criterion emerges, the mobility criterion defined as the ratio of the numbers of degrees of freedom between the considered model and the reference one, so defined as follows :

$$\mu_{mobility} = Mobility(Skel^M)/Mobility(Skel^{M-ref}) \quad (8)$$

where *Mobility* defines the number of degrees of freedom of the corresponding skeletal structure. This kind of physical criterion can also be applied to consistent subsystems, typically in the skeletal system case, to each limb. The Fig. 3 skeletal system can be interpreted as a main branched kinematic chain whose origin is located at the bottom of the trunk. This leads to naturally distinguish the spine and the head from the upper and lower limbs. However, due to their complexity and functional importance, we will consider separately hand and foot. Furthermore, because our kinematic analysis will privilege the skeleton mobility the chest specific mobility will be not considered. The mobility computation is based on classical mechanisms theory and particularly on the application of the Grübler-Kutzbach formula to each kinematic chain. A major difficulty must however be taken into account : the necessity to highlight and to quantify the joint redundancy specific to certain sub-chains of a given limb; if this is generally easy to do, some cases can be problematic, in particular the spine : although it is well known that vertebra spherical joint move in a coordinate manner, this is the repetition of small coordinated spherical-type movements which gives its surprising softness to the mammal spine, so difficult to reproduce on a humanoid robot. Despite that, to be coherent in our mobility analysis, we have considered the vertebra coordinated movements as joint redundancies and in consequence we have given 6 d.o.f. to the spine (3 for the torsal spine and 3 for the lumbar spine) and 3 d.o.f. for the neck (or head). Table 3 synthesizes the computation of the mobility criterion of each limb of our reference model (see our analysis [6] for the upper arm mobility estimation) that we have put in comparison with four actual well-known humanoid robots : Honda P2 and ASIMO, HRP-3 and Android Q2.

Limb	Ref. model	Honda P2 (1998)	Honda ASIMO (2005)	HRP-3 (2005)	Android Repliee Q2 (2005)
Spine	6	0 (0%)	1 (17%)	2 (34%)	4 (67%)
Head	3	0 (0%)	3 (100%)	2 (67%)	3 (100%)
Arm	9	7 (78%)	7 (78%)	7 (78%)	9 (100%)
Hand	23	2 (9%)	2(9%)	2(9%)	3(13%)
Leg	7	6 (86%)	6 (86%)	6 (86%)	0 (0%)
Foot	22	0 (0%)	0 (0%)	0 (0%)	0 (0%)

Table 3. Mobility comparison between Fig. 2 reference model and some actual humanoid robots.

The specific joint complexity clearly highlighted in Fig. 3 scheme is now rigorously quantified, and it clearly appears from Table 3 that actual humanoid robots are still far from mimicking their corresponding mobility. In particular it is interesting to note the null anthropomorphism level of actual humanoid robot feet. This can be explained by a double reason :

- A technical reason : foot surface participates to walking equilibrium; jointed feet can considerably increase the control problem of this equilibrium;
- A a-priori theoretical reason : kinematic complexity of hands is devoted to manipulation; because it is not for human feet – in opposition to big monkeys – foot kinematic complexity has no reason to be mimicked in human-like machines.

We think that this last point is debatable : if the nature has preserved the human foot kinematic complexity, we can think that it has its utility, in particular to adapt human walking to a large range of contact sole-ground. According to us this is a main interest of a mathematical theory of anthropomorphism : highlighting the relative importance of any element of a physiological system. In the case of this first human skeletal system analysis, it clearly appears that, besides the well-known major problem of providing hands to humanoid robots with a mobility close to the one of human hand – mimicking the kinematic possibilities of human spine and foot is a future challenge for human-like machines.

4 Limit of the local Anthropomorphism

As shown in section 3, the anthropomorphism of actual humanoid robots appears to be fundamentally a local anthropomorphism generally limited to a skeletal system anthropomorphism. It is notably important to note that the non-biomimetic electric motor is actually almost the only considered actuation mode. What are the consequences of this limited local anthropomorphism ?

We will not try to explicitly answer to the question but we want to show that it is related to a major difficulty of machines anthropomorphism : the interdependency of physiological systems limits the biomimetism of any local anthropomorphism. In other words, each physiological system can be viewed as a piece of puzzle : its specificity must be understood in relation with all other systems. For example, an anthropomorphism of the skeletal system of high level seems to give a general holonomy property to all limb movements associated to a high manipulation ability, but these remarkable possibilities are dedicated to a 'relation life' implying a soft and secure contact with the robot environment. This is the muscular system which is dedicated to provide a global compliance to the skeletal system. Because classic actuators have not this 'natural compliance' specific to natural muscles, the anthropomorphism of actual humanoid robots limited to the skeletal system makes them much less "human-friendly' and more dangerous that they can appear. Let us now assume that we get a bio-mimetic artificial muscle as discussed in [10] and references therein. We are trying to show that the proposed systemic approach can help to understand how physiological systems combine in the consequences for the robots anthropomorphism. We will limit our analysis to the case of the two close systems : skeletal and muscular systems combining into the **musculoskeletal system**.

Skeletal muscles are aimed to mobilize the skeleton bones. In consequence, the musculature system *SMUS* can be understood as the system joining the skeleton bones by means of skeletal muscles, eventually divided into active portions of them, whose set will be noted by *MUSCLE*. The resulting real system is then :

$$SMUS \subset BONE \times BONE \times MUSCLE \qquad (9)$$

and the combination of the skeletal and muscular systems into the musculoskeletal system can be made easily by adding to the skeletal system the relations between bones and muscles. The new relational system *SKELMUS* results :

$$SKELMUS \subset BONE \times BONE \times JOINT \times MUSCLE \qquad (10)$$

Let us however note that it is necessary to add an element '*no joint*' to the set *JOINT* in order to consider the possibility of a link between bones by means of muscles independently of a given joint, as illustrated in Fig. 4. Due to the complexity of muscle attachment to bones, it is difficult to propose a simple and accurate schematic representation of the musculoskeletal system. Sagittal representation appears in this case well adapted, as illustrated in limited elbow joint musculoskeletal subsystem of Fig. 4 : the concerned bones are represented by nodes, the acting muscles by full line links oriented from muscle origins to muscle extremities and joints by dotted arrows (*HU* is for humeral-ulnar joint, *HR* for humeral-radial joint and *RU* for radio-ulnar joint). Associated Table 4 specifies the respective parts of the considered muscles in the four corresponding elementary elbow motions : flexion, extension, pronation and supination.

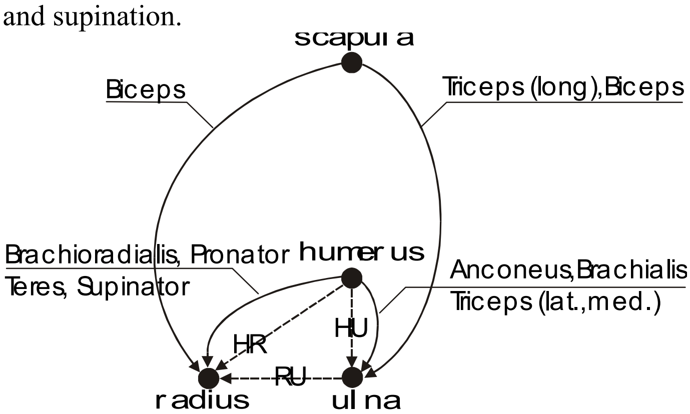
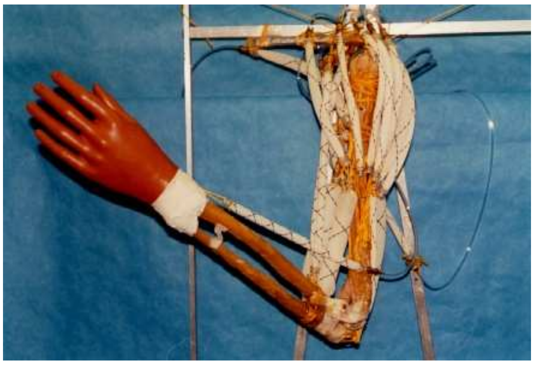


Fig. 4. Sagittal diagram of the elbow joint musculoskeletal subsystem (see text).

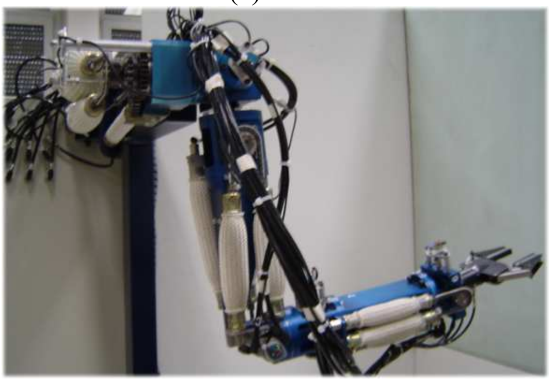
Flexion	*Extension*		*Pronation*	*Supination*
Brachialis Biceps Brachioradialis Anconeus (as initiator and dyn. stabilizer)	Triceps		Pronator Quad. Pronator Teres	Biceps Supinator

Table 4. Elbow muscles function (from [7] and [8]).

This scheme highlights a specificity of the muscle system : its apparent natural redundancy. If we combine the skeletal system and the muscular system into the musculoskeletal system, this actuation redundancy appears to be well real: whatever the joint, one muscle is necessary to perform one elementary motion in flexion, extension, abduction, adduction, external and internal rotation and yet more than the number of muscles imposed by this rule is generally used to actuate a given joint. For example, as emphasized in Table 4, it is generally considered that five muscle can participate to the elbow flexion-extension - three for the flexion and two for the extension. The Fig. 4.a arm developed at the Washington's BioRobotics Laboratory can be viewed as an attempt to mimic this complex upper limb musculature by means of McKibben-type pneumatic artificial muscles. At our knowledge no control has been developed for this robot-arm. In a different way, Fig. 4.b shows our 7R anthropomorphic robot-arm whose each of the seven joint is actuated by a pair of McKibben pneumatic antagonistic artificial muscles. Our prototype renounces to the redundancy muscular principle to consider the antagonistic artificial muscle actuator like a conventional actuator : one actuator for one robot joint. However, in recent experiments, we have highlighted the difficulty to control this arm in a vertical plane i.e. in the gravity field.



(a)



(b)

Fig. 5. Biomimetic robot-arms examples (see text).

The development of artificial muscles mimicking the phenomenological behavior of skeletal muscles is an active field of the biomimetic robotics : artificial muscles are aimed to give the 'natural compliance' to the robot joints which is lacking with classic actuators. However the anthropomorphic musculoskeletal system emphasizes the part of specific muscular redundancy. If we apply the general equation (7) anthropomorphic measurement to our non-muscular redundant 7R robot-arm we get for each of the two elbow degrees of freedom:

$$\begin{cases} \mu_{elbow\ musculature\ flexion/ext.} = 2/5 \\ \mu_{elbow\ musculature\ \mathrm{pronosupination}} = 2/4 \end{cases} \quad (11)$$

We think that muscular redundancy is related to gravity and dynamic compensation – in particular in the case of the flexion movement – and that these weak values could explain specific joint control difficulties.

This preliminary analysis suggests, besides the purely actuator biomimetism – more related to the **neuromuscular system** – the importance of the musculature structure and beyond the necessity of a good understanding of local anthropomorphisms interdependency for a valuable design of human-like machines.

4 Conclusion

Human-like machines – and typically humanoid robots – have been recently developed on the base of a purely intuitive anthropomorphism. We think that a theory of anthropomorphism could be a valuable help for the future development of more and more complex human-like machines. We have tried to highlight the relevance of the set-theory based systemic approach in the definition of an anthropomorphism of physiological systems. The application of this mathematical approach to skeletal system and musculoskeletal system can lead, according to us, to a rigorous design of corresponding systems reference models and to measure the distance between them and a developed prototype. Future work will try to highlight other potentialities of the considered theory using in particular graph theory in the study of defined relational systems.

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