FUNDAMENTAL BIOROBOTICS OF INHERENTLY LIFELIKE MACHINES

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ABSTRACT

An original way to define, analyze and design mechanical systems with inherently lifelike dynamic properties is presented. The construction of elementary actuating mechanisms for robotic manipulators which embody a complete set of technologically relevant biological principles is outlined. The ultimate objective is to develop a new class of mobile, autonomous, and interactive machines which dynamically emulates live musculoskeletal systems.

This study introduces the mathematical models and algorithms to transform and synthesize the results of research in musculoskeletal physiology into explicit engineering design specifications. The application of a new contractile muscle-like viscoelastic motor as a servomechanical drive for articulated rigid link mechanisms is investigated. Key features of the neuromuscular force control by twitch summation are combined to formulate a pulse stream control method suitable for fluid powered mechanisms.

Biorobotique fondamentale des machines
qui modèlent les système musculaires.

Cette étude présente une nouvelle méthode d'analyse et de conception des systèmes mécaniques dont les caractéristiques sont semblable aux êtres vivants. Les exemples de construction des éléments des mécanismes robotiques ont été choisis pour illustrer l'application de la totalité des principes biologiques, technologiquement significatifs. L'objectif ultime est le développement des machines autonomes et interactives qui reproduisent spontanément la dynamique des systèmes musculaires.

Les nouveaux modèles mathématiques et les algorithmes sont introduits afin de permettre l'utilisation des résultats des recherches en physiologie et en biomécanique dans la préparation des devis techniques pour la construction mécanique. Les applications d'un servomoteur viscoélastique et contractile sont également examinées dans le domaine des bras aux articulations conventionnelles. Les propriétés principales de la commande neuromusculaire ont inspiré la conception d'un système de contrôle des moteurs hydrauliques par pulsations variables.

INTRODUCTION

Norbert Wiener's "Cybernetics" [1], a successful comparative study of control and communications in live systems and machines, is now half-a-century old. However, it is disappointing that our robots are still comparatively deaf, blind, clumsy and run by "inflexible action programs essentially differing from those of the human or mammalian nervous system", as noted by Prof. Morecki [2]. Although unsubstantiated by experience or well founded inference, it is commonly accepted that all required performance improvements will arise automatically with faster processors, larger memory capacities and more advanced control algorithms but without radical evolution of mechanical hardware concepts.

There is evidence [3] to indicate that computerized instrumentation and controls cannot stimulate a conventional manipulator to attain the behaviour of a live musculoskeletal system. The argument that live movements can be recorded and their kinematic copies accurately reproduced is misleading. One tends to overlook the viscoelastic nature of muscle tissues that spontaneously filters the power output of every joint of a live limb, through spontaneous energy storage-release cycles, to effect the characteristic output torques and accelerations. The amount of stiffness-controlled actuating power is determined by interaction between the joint stiffness and a generally unknown position-velocity-acceleration and, often, time-dependent, external load. No control system, unless clairvoyant, can determine the instantaneous dynamic features of an external load, that controlled joint acts upon, on the bases of past history of motion, torque and control signals. Without ability to predict the load, a controller cannot improvise a real-time choreography of non-biorobotic joints that would emulate lifelike torque-displacement-velocity behaviour.

Rather than relinquishing all responsibility to artificial intelligence as yet unrealized, mechanical engineers must recognize that successful autonomous, mobile and interactive robotics will depend on how closely we follow nature's own division of control functions and inherent mechanical responses. Lifelike robots will require new design concepts that differ from those of traditional machinery as much as integrated electronics and advanced software differ from hard-wired relay logic technology. The definition of the term *biorobotics,* in this review, was stated by the author in 1988 [4] as: *"An interdisciplinary engineering field specialized in systematic applications of the complete sets of mechanically relevant biological principles in the construction of conceptually balanced, mobile, autonomous and interactive robots"*. A *conceptual balance*, in this study, refers to the combination of subsystem *conceptual levels* for which the performance of every subsystem is optimized. *Conceptual level* is the extent to which a particular subsystem is inherently adaptable to automatic operation. Any machine, joint, actuator or a control system referred to as "biorobotic" must inherently emulate all technologically relevant biological principles and have a conceptually balanced design for mobile, autonomous and interactive applications. Interactive machines in biorobotic terms will be those that can not only perceive changes in the environment and adapt to them, but also spontaneously interact with any external load in a lifelike manner.

Finally, what are practical reasons for constructing inherently lifelike robots when machines can be stronger and faster than any living system? Besides improving motorized prostheses and lucrative "Disneyland engineering" robotics, lifelike machines could automate an endless variety of industrial and domestic tasks that are still exclusively manual. The apparent speed and strength of an industrial robot are achieved at the expense of versatility, strength/mass ratio, mobility and autonomy. A combined performance evaluation, that equally weights these four properties, favours the human labourer by a score of almost 27:1. (A typical 6 DOF machine offers only 5% of the DOFs of all four human limbs [2], a good robot features about 10% of a human's payload-to-mass ratio, [5], while the mobility and autonomy of such manipulators are zero.) Furthermore, it is believed that only inherently lifelike machines could be, eventually, "taught biorobotically" to acquire difficult manual skills directly from reliably detected myoelectric signals of a human or an animal in the process of performing any task.

Here is an outline of one approach to define, analyse and design such systems. This is a highly condensed digest abstracted from [3] & [4] in order to produce an article of reasonable length from a body of work which, though imperfect, was based on over fifteen years of research and experiment.

DYNAMIC MODELLING WITH BIOROBOTIC FUNCTIONAL

A biorobotic joint, Fig.1(a), must generate the same torque-velocity-displacement $(T\text{-}\omega\text{-}\theta)$ actuating profiles as the corresponding live model, Fig.1(c), when both joints act against an identical load $L(\theta,\omega,\alpha)$, Fig.1(b), and under identical control signals or stimuli $S_i(\theta,t)$. The stimulus, $0 \le S_i \le 1$, defines the *level of activation*. (Muscle develops maximum force at a given rate of contraction when $S_i=1$.) When n muscles are involved, the integer i, $1 \le i \le n$, indicates that variable is associated with i-th muscle.

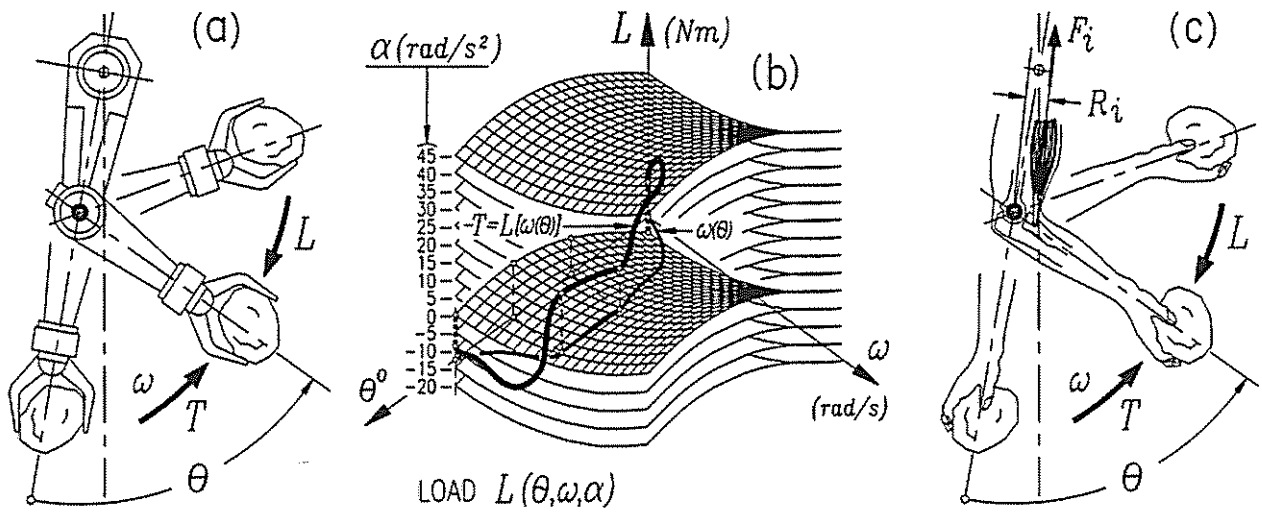


Figure 1: a) Biorobotic joint; b) Load model $L(\theta,\omega,\alpha)$ with an example of one $\omega(\theta)$ function and the corresponding $L[\omega(\theta)]$ space curve; c) Emulated live joint.

Joint torque, $T=\sum T_i = -L$, includes responses of stimulated and relaxed antagonists - extensors in flexing mode and vice-versa. When some load properties vary accordingly to a separate clock, t_L, the time t_L is observed as an independent variable. Furthermore, some load components may be also viscoelastic turning the function L into a functional, $\mathscr{L}$, and leading to the generalized torque equation (01).

$$T = \sum_{i=1}^{n} S_i T_{imax} = \sum_{i=1}^{n} - \mathscr{L}_i \left(\theta,\omega,\alpha,t_L\right)_{t=-\infty}^{t} \tag{01}$$

Relationship between the three sets of variables S_i-L_i-T_i is governed by a Biorobotic functional $\mathscr{B}$, see Fig.2, meaning that a momentary status of a joint actuating process is determined by the entire history of S-θ-ω-α & J_D. (α and $J_D=\sum J_{Di}$ are, respectively, the joint angular acceleration and dynamic stiffness defined in more details later on.) The domain of variables of this deceptively simple-looking functional represents a summary of all non-redundant biomechanical models of live tissues relevant in biorobotic analysis. In mathematical terms, biorobotic functional symbolizes a non-linear system of equations critical for operation of a live joint. Since many biomechanical functions are simply collections of tabulated experimental readings, there are no closed-form solutions for any actuating profile variable. A biorobotic actuating process must be analyzed either by means of dedicated analog computing circuits or by iterative computing algorithms.

When the mechanical properties of muscle are described by a "three-element" model (Fig.3) proposed by A.V. Hill [6], or by any enhanced version thereof, the force and motion generating process is shown as *contractile element* (CE) in series with a *series elastic element* (SE). A structurally independent *parallel elastic element* (PE) is parallel to CE-SE tandem. The "elastic elements" SE and PE are, in fact, two viscoelastic subnetworks represented by classical Kelvin-bodies VS-ηS-SS and

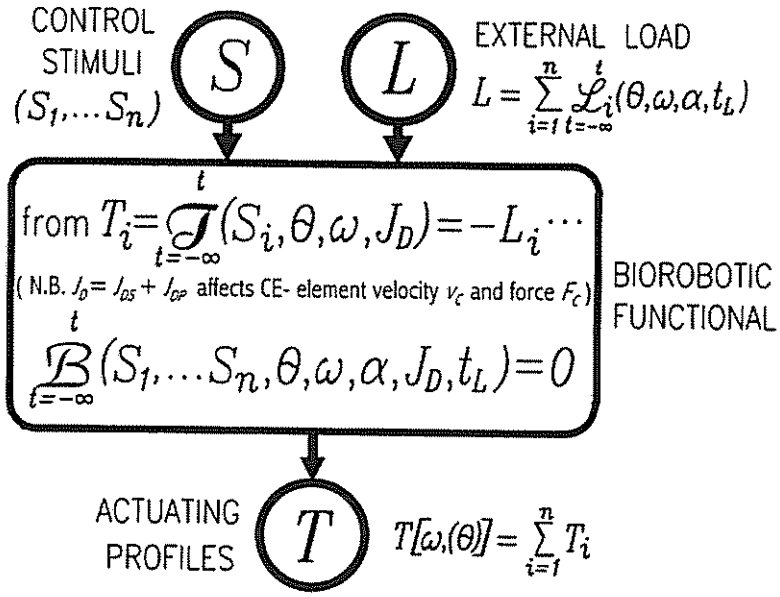


Figure 2: Biorobotic functional of an actuating process.

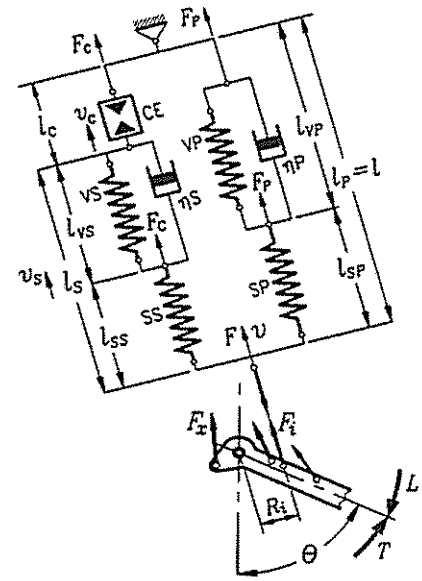


Figure 3: CE-SE-PE dynamic model of a live muscle.

VP-ηP-SP or by some more refined models. Muscle-generated torques depend on the entire history of actuating process even under isometric conditions. Dynamic stiffness J_{Di} is defined by Eq.(02).

$$J_{Di}= = \frac{dT_{Si}}{d\theta_{JSi}} + \frac{dT_{Pi}}{d\theta} \quad \ldots \quad \text{when} \quad \ldots \tag{02}$$

$$\ldots \quad \theta_{JSi} = \int \frac{dl_{Si}}{R_i} \quad ; \quad \omega_{JSi} = \frac{d\theta_{JSi}}{dt} \neq 0 \quad \ldots \quad \text{and/or} \quad \ldots \quad \omega_{JPi} = \frac{d\theta}{dt} \neq 0$$

In formulating procedure for computing T-α-ω-θ-J_D output of an actuating process using a biorobotic functional, the elements of functional domain are schematically represented within a simplified set of functional pathways. An illustration of adopted mapping method of the variables associated with (i-th) joint muscle is given in Fig.4 where θ, ω, α and t_L, as functional arguments, yield the load L. Angle θ is obtained by integrating displacements ωdt at point ①. ω is obtained, from αdt at point ②. Acceleration α is determined at ③ from T, L and L_0, where $L_0=L(\theta,\omega,t)$ for $\alpha=0$. Torque T implicates all muscle forces $F_i=F_{Pi}(l_{SPi})+F_{Ci}(S_i,l_i,v_{Ci})$ and their moment arms $R_i(\theta)$. This brings into play the forces of all contractile and parallel elements, their lengths, linear velocities, viscous and elastic coefficients and other related variables.

Such a phenomenologically descriptive schematic of the working relationship among the elements of biorobotic functional helps to visualize the physical structure of the domain, however, all the functions must be further broken down into single arguments and mapped in a computational network where each variable appears only once. The entire original maze of various mathematical and empirical models, outlined by functional pathways in Fig.4, is reformatted into a new engineering modelling network, Fig.5, called *The Functional Network of Biorobotic Variables*, or *FNBV*. The network nodes represent various physiological, kinematic and dynamic properties involved in an actuating process, while the links define their functional relationships. FNBV links are directed because the variables represented on an

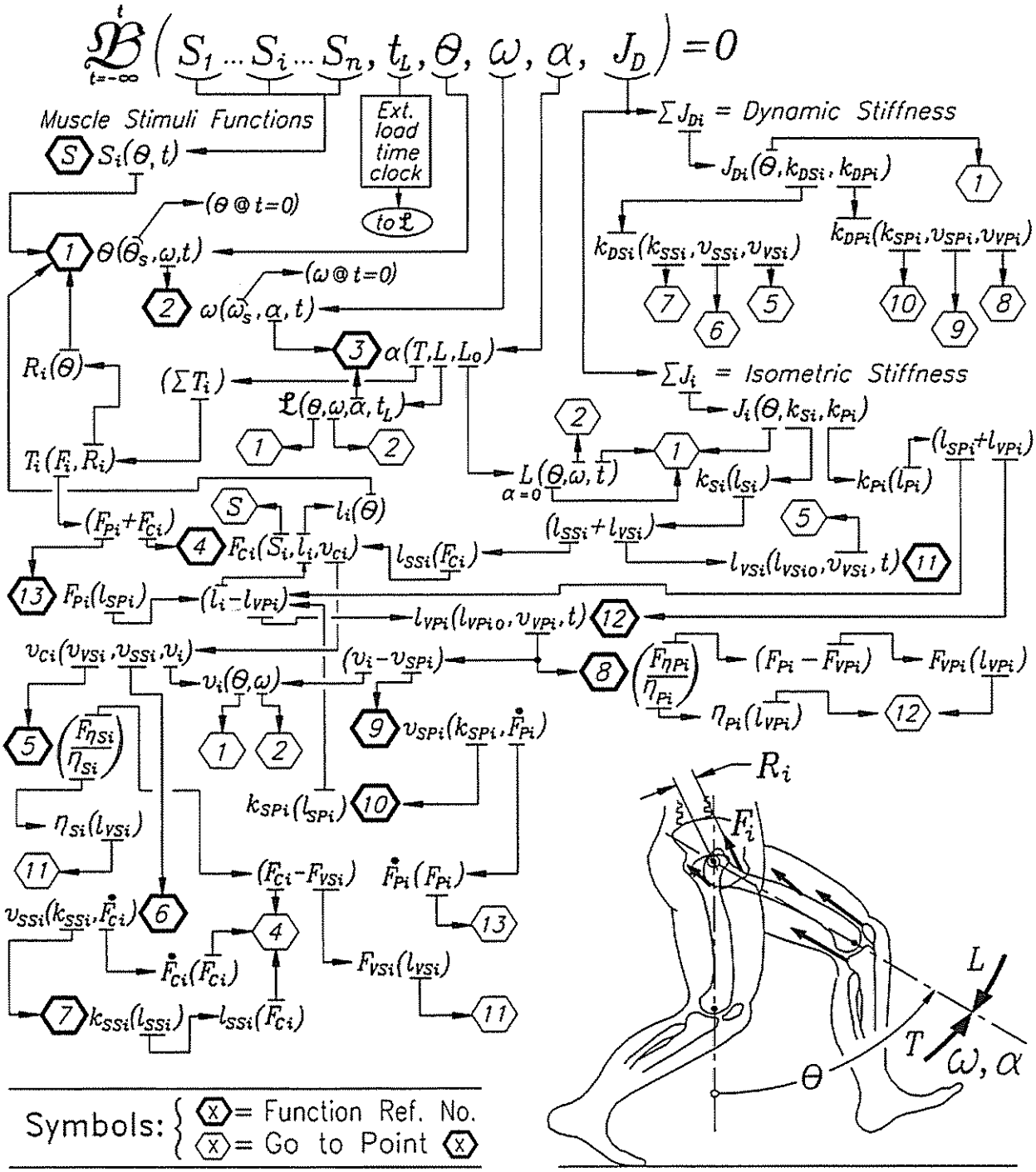


Figure 4: Live joint domain of a biorobotic functional

FNBV have to be processed by iterative algorithms in a functionally logical order similar to the processing of mutually dependent construction activities on a CPM chart. For example, spring rate k_{SSi} is determined directly from the SS element length l_{SSi} , however, one cannot find l_{SSi} from k_{SSi} although an inverse function, $l_{SSi}(k_{SSi})$, exists. The length l_{SSi} is physically determined by the force of

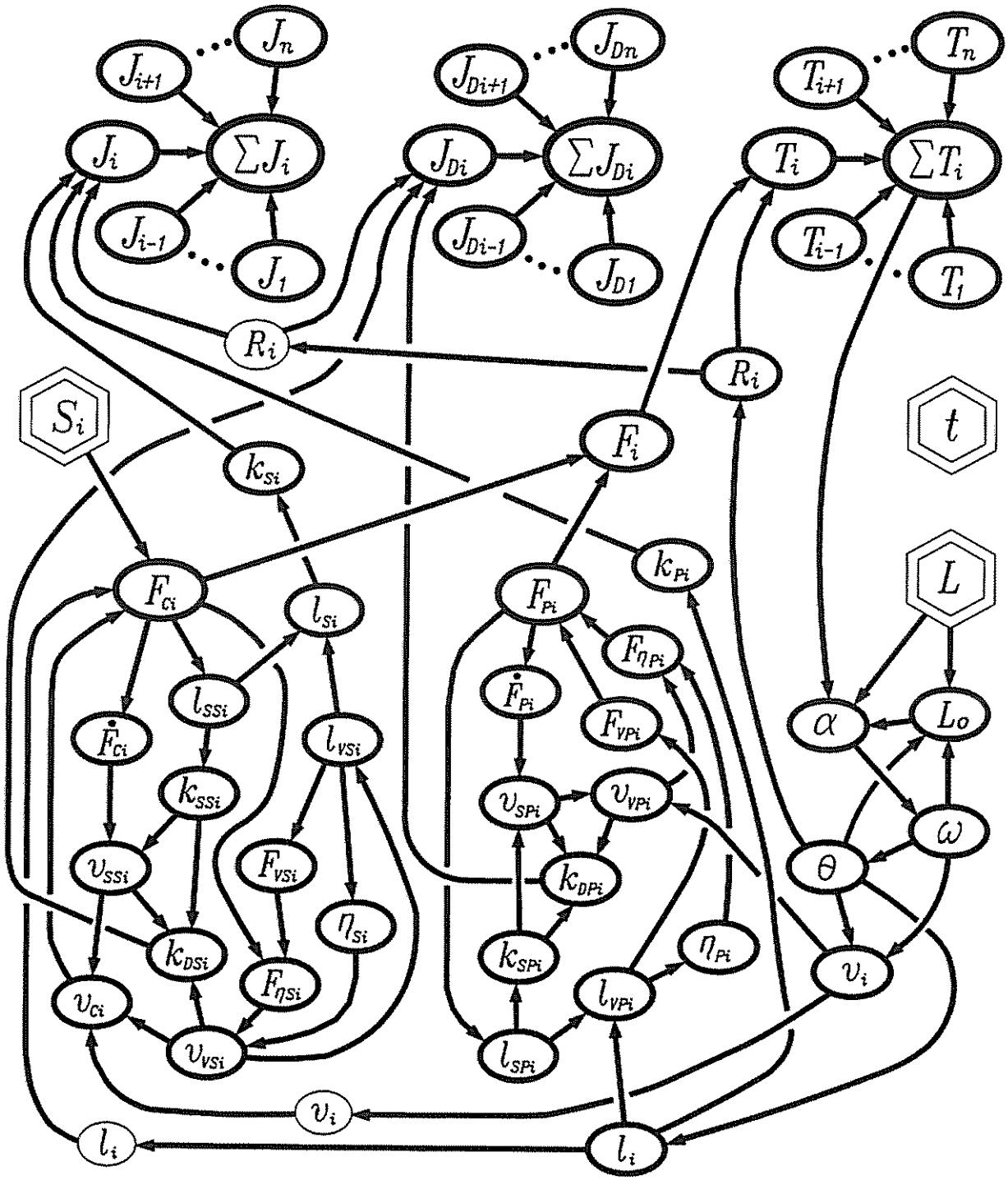


Figure 5: Functional Network of Biorobotic Variables (FNBV)

the contractile element F_{Ci} which is affected indirectly by k_{SSi} through v_{Ci} in combination with l_i and S_i. All the variables within an FNBV are mutually dependent and, at any time, there can be only one set of instantaneous values of these variables that satisfies the process boundary conditions and history of the load and stimuli inputs.

Overall active torque T is the sum of n torques contributed by n muscles. Similar summations apply to the isometric and dynamic link stiffness J and J_D. Within an FNBV, T, L and L_0 yield α, ω and θ. Consequently, the momentary muscle length l_i, velocities v_i and forces F_{Ci} can be computed.

FNBV fully defines the entire torque and stiffness development process and serves as an algorithm template for internal and external actuating dynamics of a live viscoelastic joint. FNBV can be used to compose a great variety of iterative algorithms to compute, for example, $L(t)$ from a known $\theta(t)$ and a set of S_i; to find $S_i(t)$ that produce an $\alpha(t)$ under a given $L(\theta,\omega,\alpha,t)$; to determine $T(\theta,\omega,)$ that suits a prescribed $J_D(t)$, etc.

FOUR ESSENTIAL BIOROBOTIC PROPERTIES

Industrial designers cannot copy detailed anatomy and physiology of musculoskeletal systems with existing engineering materials and manufacturing techniques, but they can develop mechanisms that offer comparable active and passive mechanical responses. Actuating process defined by a biorobotic functional can be translated into explicit joint performance specifications represented by visualizable threedimensional models by extracting the following four mechanical properties: 1) Isometric torque function $T_o(\theta)$; 2) Isotonic torque v/s velocity characteristic $T(\omega)$; 3) Nominal dynamic series stiffness $J_{DS(N)}(\theta, \theta_{JS}, \omega_{JS})$; and 4) Nominal dynamic parallel stiffness $J_{DP(N)}(\theta, \omega)$. These four properties, Fig.6(a),(b),(c) & (d), fully describe the active force development process within CE (essential properties No. 1 & 2) as well as the passive responses of all muscle tissues in series with, or parallel to, CE (essential properties No. 3 & 4). Proposed division of mechanically relevant joint characteristics is valid for any dynamic model that we may choose, eventually, to represent the live actuators.

These four properties define *an isotonic dynamic model (IDM)*, shown in Fig.6(e) as solid $T(S, \theta, \omega)$, and *a nominal dynamic stiffness model (NDSM)* shown in Fig.6(f) as solid $J_{D(N)}(\theta, \theta_{JS}, \omega)$. Two models represent the joint dynamics in a generalized biorobotic actuating torque functional. Any joint designed with these inherent properties yields a lifelike *actuating profile* $T[\omega(\theta)]$ through a spontaneous dynamic equilibrium $T=-L$. The four essential actuating properties constitute *"all mechanically relevant biophysical principles"* referred to in the definition of biorobotics and they should be inherent to an actuating mechanism. These properties can be provided by means of any judicious combination of mechanical designs that do not necessarily emulate all individual kinematic, physiological and dynamic features of a live musculoskeletal joint.

IDMs are computed for isotonic muscle or actuator forces, i.e. for $dF_i/dt=0$. An IDM may define contribution of an individual live or artificial actuator, or represent the $T(S_{CDM}, \theta, \omega)$ solid of a joint driven by one fictitious muscle which, acting alone produces the equivalent effects of the entire actuating system. The CE-SE-PE mechanical analog of such synthesized, single actuator will be called *compound dynamic model (CDM)*. It correctly represents the live joint under uniform stimulation and offers a fairly good initial insight into the biorobotic potential of a new joint design. Fig.6(e) illustrates a biceps IDM for an average live supinated forearm flexing in a parasagittal plane. The top surface of this IDM is obtained for $S_{BICEPS}=1$. Constant sub-maximal stimuli produce $T(\theta, \omega)$ surfaces located between IDM's top surface and θ, ω plane. When IDM angular velocities, at a given shoulder joint displacement, are computed for zero joint friction and zero forearm mass, the model does not depend on the body position. Static and dynamic forearm dead loads are then included in load function.

The *nominal dynamic stiffness* in this study has been defined as *the instantaneous change in rate of internal energy transfer per unit elastic deformation of a joint, measured upon executing a fixed amount of such deformation at a constant rate of displacement.* For example, nominal series dynamic stiffness, $J_{DS(N)}=dT_S/d\theta_{JS}$ at a θ_{JS} and for an ω_{JS}, would be $J_{DS(N)}$ found at $\theta_{JS}+\theta_{JS(N)}$ when a small deformation $\theta_{JS(N)}$ is reached under a constant rate of deformation ω_{JS}. The viscoelastic model is assumed

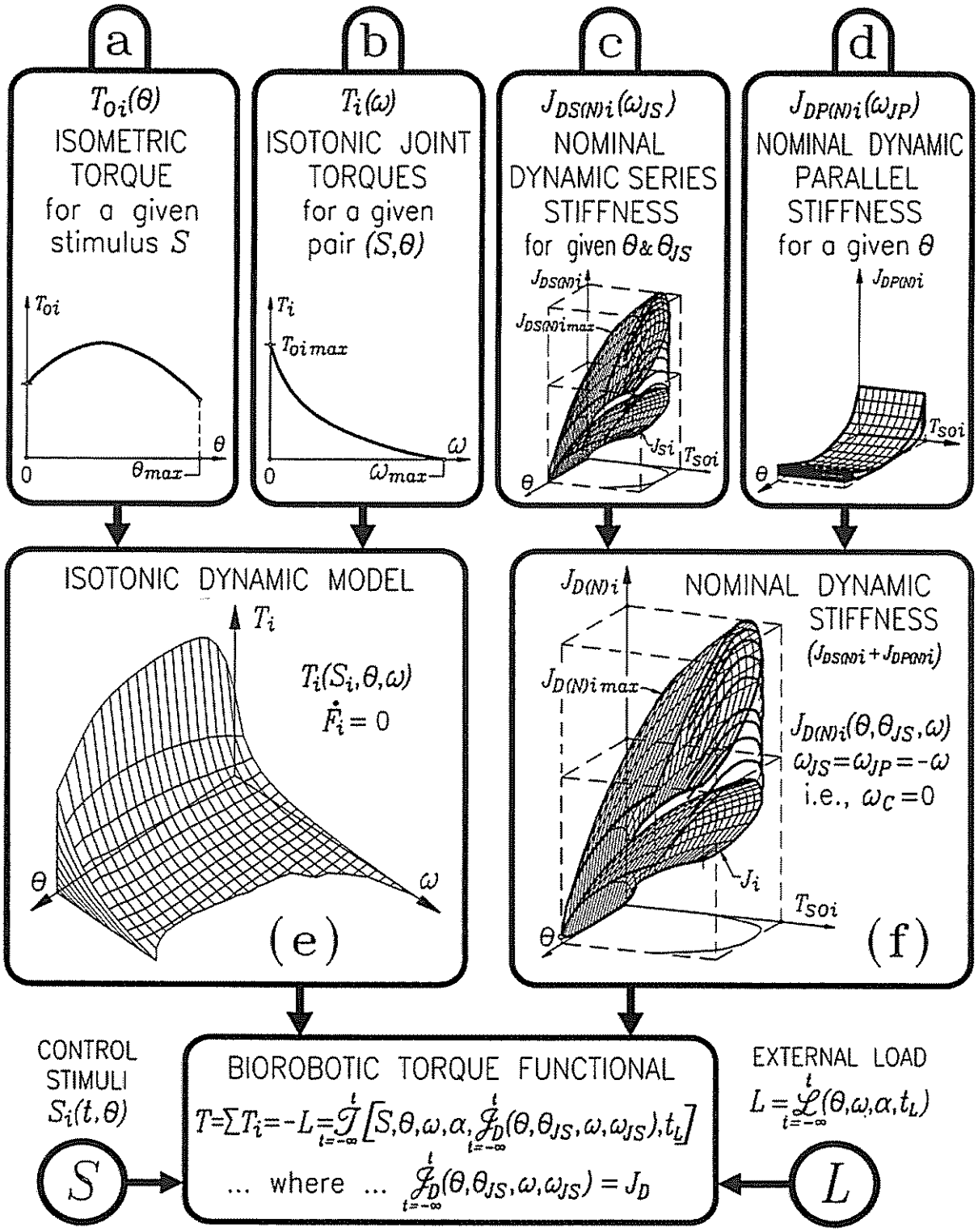


Figure 6: (a,b,c, & d) Four essential biorobotic properties associated with i-th joint actuator
(e & f) Biorobotically relevant dynamic models

to be under stable isometric conditions at θ_{JS}. Under similar conditions, the nominal parallel dynamic stiffness $J_{DP(N)}=dT_P/d\theta_{JP}$ is found at $\theta_{JP}+\theta_{JP(N)}$ for an $\omega_{JP}=\omega$. Torques T_S and T_P are those supported by SE and PE elements while the joint rotations and angular velocities θ_{JS} & ω_{JS} and $\theta_{JP}=\theta$ & $\omega_{JP}=\omega$ are associated with the changes in length of SE and PE. The nominal dynamic joint stiffness $J_{DS(N)}$ or $J_{DP(N)}$ can be alternatively defined as the momentary stiffness measured at θ_{JS} or θ, upon rotating the joint at a constant speed from $\theta_{JS}\pm\theta_{JS(N)}$ or $\theta\pm\theta_{JP(N)}$ where SE and PE were stable.

Although ω_{JS} and ω_{JP} are independent variables in a generalized stiffness model $J_D(\theta,\theta_{JS},\omega_{JP},\omega_{JS})$, a three-dimensional projection of this four-dimensional stiffness model is available whenever the length of the contractile element CE, l_C in Fig.3, is kept constant, i.e., when $\omega_{JS}=\omega_{JP}=\omega$. $J_{DS(N)}$ and $J_{DP(N)}$ are then combined into one nominal dynamic stiffness model $J_{D(N)}(\theta,\theta_{JS},\omega)$ or $J_{D(N)}(\theta,T_{S0},\omega)$. T_{S0} is the static torque T_S required to produce θ_{JS}.

A robotic joint that emulates live $J_{DS(N)}$ and $J_{DP(N)}$ models will have lifelike amounts and rates of potential energy storage and release during an actuating process. It has been shown [3] that $J_{DS(N)}$ and $J_{DP(N)}$ can be computed using the equations (03) and (04) where k_{SS}, k_{VS}, k_{SP} & k_{VP} are the instantaneous spring rates of elastic elements SS, VS, SP & VP and η_S & η_P are the instantaneous damping coefficients of viscous elements ηS & ηP.

$$J_{DS(N)}=\frac{k_{SS}R^2}{k_{SS}+k_{VS}}\left[k_{VS}+k_{SS}e^{-\frac{\theta_{JS(N)}(k_{SS}+k_{VS})}{\eta_S\,\omega_{JS}}}\right] \tag{03}$$

$$J_{DP(N)}=\frac{k_{SP}R^2}{k_{SP}+k_{VP}}\left[k_{VP}+k_{SP}e^{-\frac{\theta_{JP(N)}(k_{SP}+k_{VP})}{\eta_P\,\omega_{JP}}}\right] \tag{04}$$

Once the four essential biorobotic properties are determined for any joint, a variety of practical models can be derived for CAD applications. Here are some examples:

Parametric Dynamic Models (PDMs) are the IDMs with all T_{max}, ω_{max} and θ_{max} normalized to 1. A PDM is suitable for qualitative comparison or evaluation of lifelikeness of any particular type of joint actuating system. The properties of isometric and isotonic lifelikeness are inherent to a given type of drive and they cannot be qualitatively altered by changing design parameters. Furthermore, actuating properties not contained in a PDM, are all stiffness related and cannot be used to compensate any IDM deficiencies.

Constant Acceleration States Models (CASMs) are the continua of $T[\omega(\theta)]$ functions determined for constant accelerations α. These space curves are obtained by superimposing an IDM and an *external load model* $L(\theta,\omega,\alpha)$ to create intersections of $T(\theta,\omega)$ and $L(\theta,\omega)$ surfaces for, respectively, a constant S and a constant α. Tabulated as $\alpha(T,\theta,\omega)$ arrays, CASM data provide instantaneous isotonic accelerations for any kind of joint dynamics.

Kinematic Models (KMs) are $\alpha(S,\theta,\omega)$ solids obtained from CASMs that yield the $T[\theta(\omega)]$ functions for any pair of S and α. We transform a CASM into a KM by computing a function or array $\alpha(S)$ for all (θ,ω) pairs. KM treats joint actuation as a kinematic process since the load and drive dynamics are accounted for in the KM solid. KM based kinematics offers a valid isotonic reference or a low joint velocity approximation.

Dynamic Control Models (CDMs) are $S(S_{LIVE},\theta,\omega)$ solids where S_{LIVE} and S are, respectively, the control stimuli of a live and an artificial, non-biorobotic, joint that produce the same joint torques when acting against the same type of load. CDMs are derived from live-artificial pairs of IDM or PDM solids and, unlike KMs, their shapes are not affected by the load functions.

INHERENTLY LIFELIKE ACTUATING HARDWARE

The inherent lifelikeness of a mechanical system, in this study, is the ability to spontaneously emulate the relationship between musculoskeletal control stimuli, external loads and actuating profiles. Therefore, a biorobotic joint cannot be made with a single actuator since all live joints are powered by several individually stimulated muscles. Even if only two muscles are flexing or extending a joint, under specified conditions $\theta_x, \omega_x, \alpha_x$ and dT_x/dt, a submaximal joint torque $T_x = S_1F_{1max}R_1 + S_2F_{2max}R_2$ can be shared in an infinite number of ways. When, e.g., $2F_{1max} = F_{2max}$ and $2R_1 = R_2$, the control combinations $[S_1=0.2 ; S_2=0.95]$ and $[S_1=0.8 ; S_2=0.8]$ produce the same active torques but totally different dynamic interaction with external load. This joint has in each case different amounts of stored energy, different rates of energy transfer and its CEs have different (S_i, l_i, v_i) inputs. Furthermore, the stimulation of antagonists, for the purposes of joint stiffness control, causes additional changes of actuating dynamics imposing some wholly unnatural control strategies for a single-actuator joint drive. At least the prime movers must be individually represented in a biorobotic mechanism. Actually, an ideal lifelike machine would even require emulation of separately controlled motor units within each muscle. For most practical application this would not be justifiable since the neuromuscular stimulation does not normally go to the extremes in deviating from a proportional load sharing among either synergetic muscles or muscle motor units. On the other hand, with exception of T_{max} conditions, when all $S_i=1$, the stimuli are, indeed, always different. In a groundbreaking biomechanical study, Seireg and Arvikar [7] pioneered a method of computing muscle forces within a statically indeterminate system by optimizing a certain set of "objective functions" that aim to minimize muscle forces, muscle work, joint reactions or joint ligament moments. (For example, the natural control system tends to simultaneously optimize a weighted sum of muscle forces and joint moments during walking, etc.)

The most critical feature of any muscle-like joint activating system is the presence of a right combination of all qualitatively lifelike actuating properties. One cannot scale, amplify, adjust or otherwise enhance the characteristics that either do not exist in a design concept, or that are not suitably interfaced in a dynamic model. The example of spontaneously contractile, liquidtight *Artificial Skeletal Muscle* <R> *(ASM)*, [3][4], illustrates the feasibility of biorobotic actuators. An axially extensible, pre-stretched anisotropic tube 1, Fig.7(a), has a circumferential wall reinforcing 2, that limits radial expansion, and it is closed by two permanently bonded artificial tendons 3 & 4. ASM actuating force is zero when the internal fluid pressure is in balance with ASM tube wall tension. Increased fluid pressure extends ASM and increases potential energy. Lowering of pressure releases elastic force which does the work when ASM contracts. The portion 2-3 of ASM's $F(l)$ function in Fig7(b), is similar to that of a human muscle in its normal working range - portion 2-4 of $F(l)$ function in Fig8(b). The lateral ASM expansion is a functional equivalent of the series elastic element because it makes the relationship between ASM contractile velocity and that of its contractile element dependent on the momentary actuating force/time derivative. Any ASM axial or radial expansion or contraction results in a fluid flow into or out of the actuator tube accompanied by viscous responses that emulate dissipative elements of active and passive muscle tissues. The CDM of an ASM driven joint, Fig.7(c), exhibits a contractile element CE and two structurally independent viscoelastic responses (SS- ηS and SP-VP-ηP) that pattern fairly well the SS-VS-ηS and SP-VP-ηP subnetworks of a live joint CDM - Fig.8(c).

PDM and isometric joint stiffness signatures of an ASM biorobotic elbow are found on self-explanatory Fig.9 and Fig.10. Experimental work and computer simulation show that an ASM design can reproduce live joint performance, under totally different types of loads, within maximum deviation of 8%. This is unequalled by any conventional joint under identical stimulus-load conditions.

Besides a unique biorobotic concept, ASM is simple and inexpensive (a fully elastomeric "throw-away-for-recycling" product with large manufacturing tolerances); it is silent and absolutely liquidtight

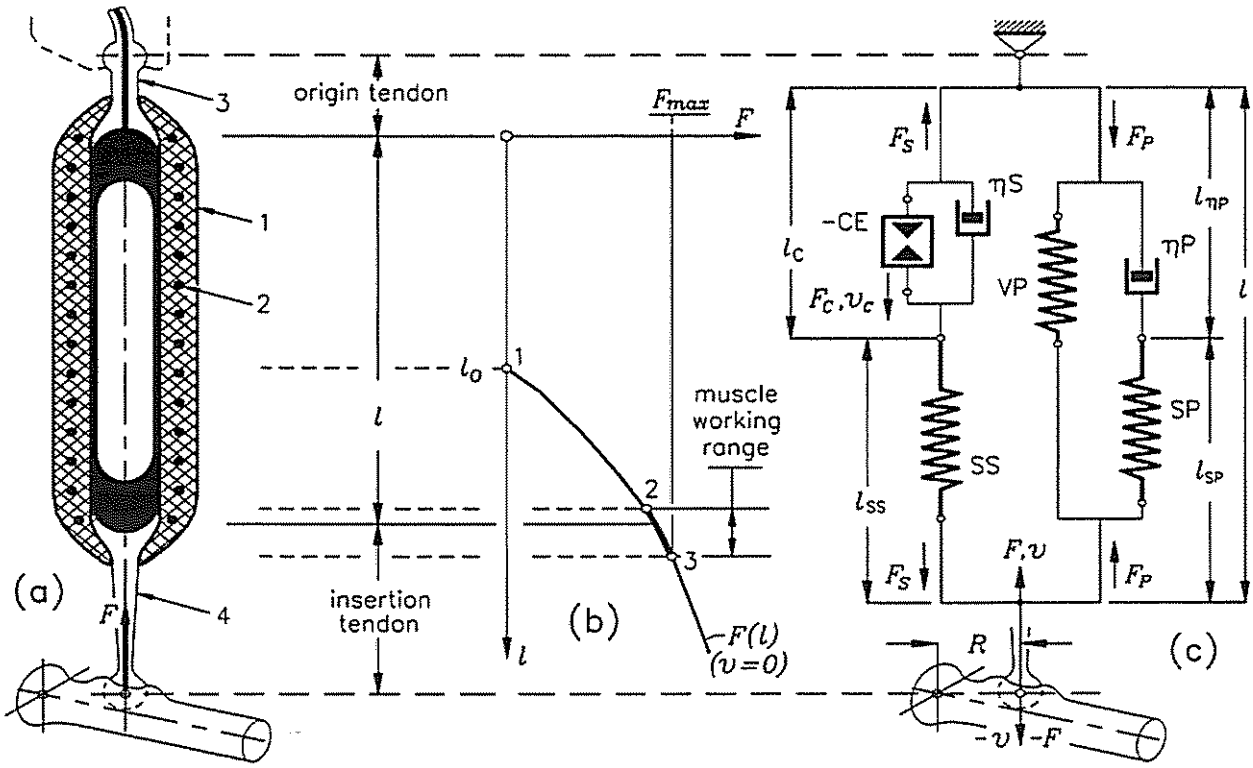


Figure 7: a) Artificial Skeletal Muscle (ASM); b) Contraction force-muscle length characteristics *F(l)*; c) Compound dynamic model (includes passive responses of antagonists)

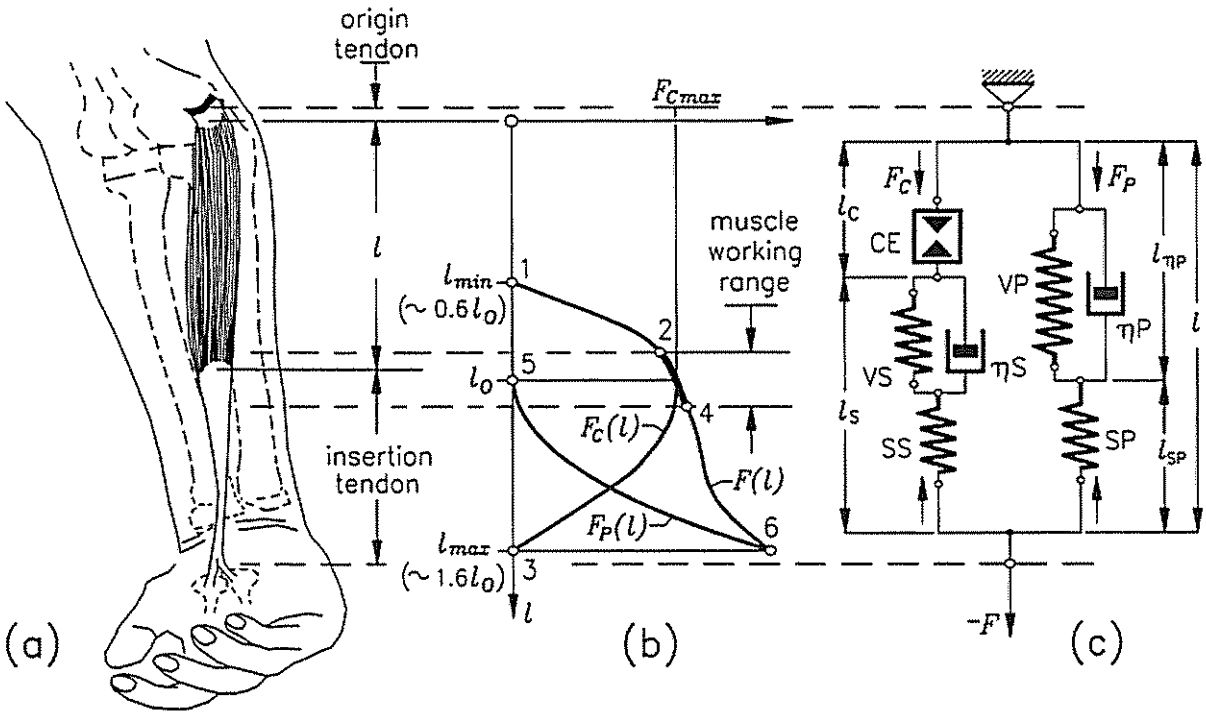


Figure 8: a) Live muscle; b) Contraction force-muscle length characteristics *F(l)*; c) Compound dynamic model (includes passive responses of antagonists)

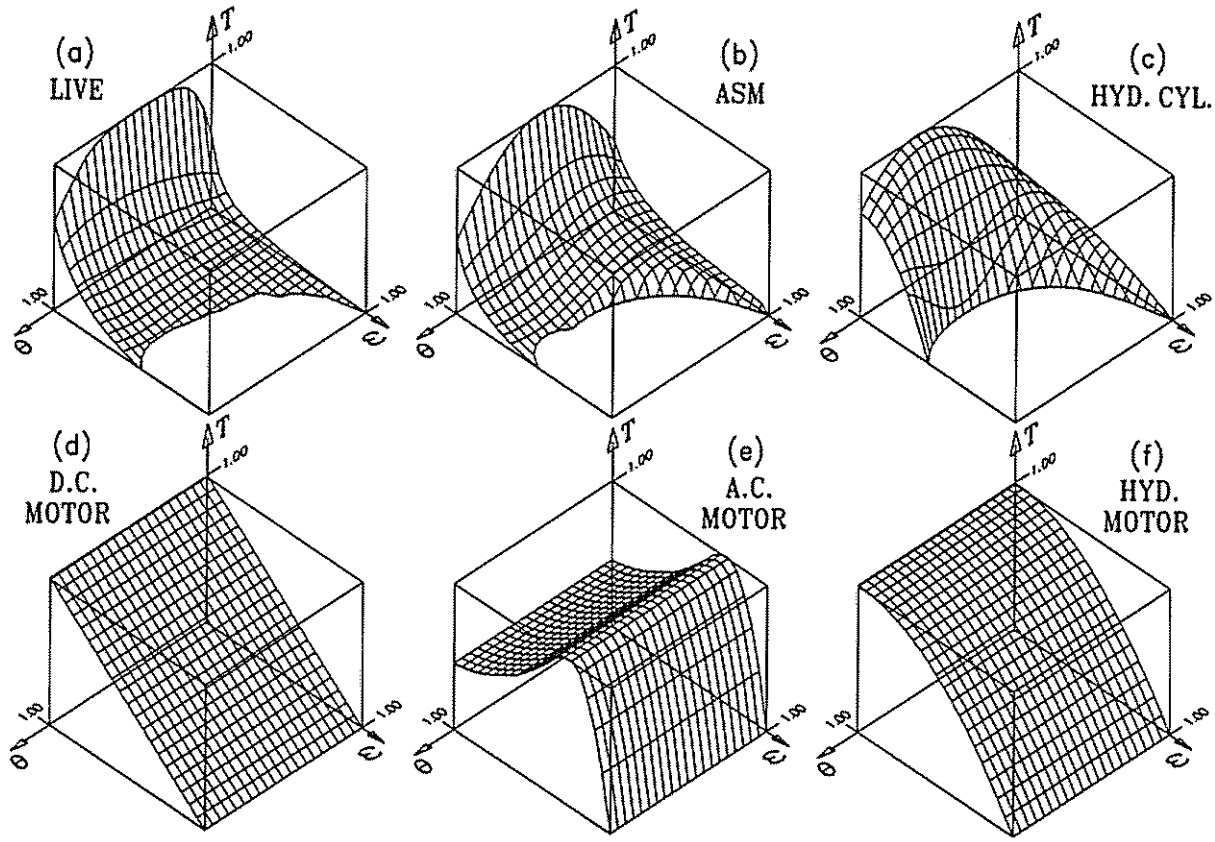


Figure 9: Parametric dynamic model of a flexing elbow joint powered by: a) Live muscles; b) ASMs; c) Hydraulic cylinders; d) D.C. motor; e) A.C. motor, and f) Hydraulic motor.

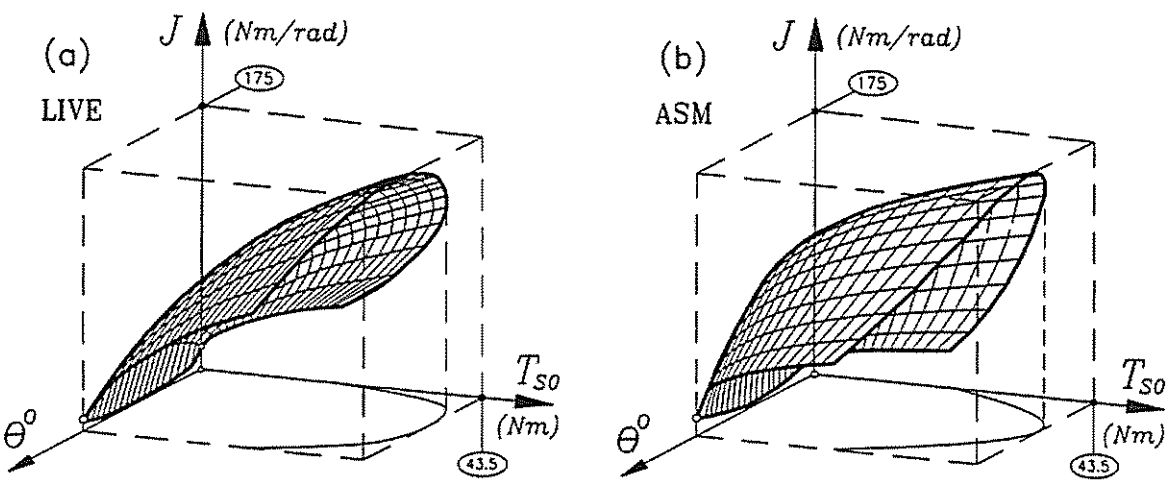


Figure 10: (a) Isometric Stiffness Model of an average live elbow for flexing output torque.
(b) Isometric Stiffness Model of an equivalent ASM joint.

(no dynamic seals) and it features low inertia, zero stiction, zero backlash, zero vibration and intrinsic compliance. ASM is laterally bendable, it stores and regenerates energy and can be moulded, when necessary, into a variety of shapes to fit special anthropomorphic configurations as illustrated in Fig.11.

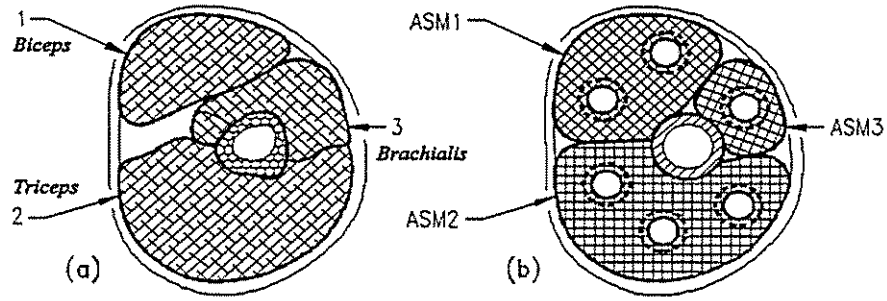


Figure 11: (a) Cross-section of a live upper arm. (b) Cross-section of an ASM-based upper arm. ASM1, 2 & 3 emulate live muscles.

BIOROBOTIC CONTROLS

In addition to inherently lifelike actuating dynamics, biorobotic machines will require control hardware which can respond to a control center that functionally emulates the neuromuscular subdivision of somatic nervous system. Here is a selection of technologically relevant biological principles that must be included in design of such control hardware :

1) The live control system can recruit any number of motor units that are available in a given muscle.
2) All motor units within this system are of different size. This increases enormously the number of available force control levels. (Seven identical motor units, for example, could produce with constant stimuli only 2^3 force magnitudes, while the same number of units, all of different size, produce 2^7.)
3) The force contributed by each recruited motor unit can be varied individually by adjusting the average frequency of the stream of *motor unit action potentials* (MUAPs) delivered by the motor unit nerve called axon. (Each MUAP is a pulse which causes one *motor unit twitch.)*
4) Stimulation of various motor units within a muscle is done by mutually asynchronous pulse streams. This contributes to the overall smoothness of the muscle force, especially when some or all of the motor units are in the state of *unfused tetanus,* i.e. when they twitch at sub-maximal frequencies.

The above natural design strategy has produced a remarkable positioning precision, a wide range of force control, smooth active forces at all levels of stimulation as well as limb stiffness control. A machine that meets the four essential biorobotic properties, outlined earlier, and that has the control application hardware designed according to the above four principles, will have controller output requirements functionally similar to those of the biological motion controls at the neocortex level. The feasibility of such biorobotic control hardware in the fluid power field is demonstrated by Asynchronous Pulse Stream Control (APSC) patented by Bubic [8] and outlined in Fig.12 where each restrictor R_i, in line with a pulsating valve, represents one *actuating unit.* Due to non-linearity of the flow-pressure function, the relationship of the flow rates, Q, of any two valves with different restrictors, for any common upstream pressure, is governed by Eq.(05).

$$Q_{i,l}(Q_{j,k}) + Q_{j,k}(Q_{i,l}) \neq Q_{i,k}(Q_{j,l}) + Q_{j,l}(Q_{i,k}) \tag{05}$$

Subscripts i and j designate the i-th and j-th valve with different restrictors. Subscripts l and k specify the l-th and k-th pulse stream waveforms. The above expression can be expanded to any number of different valves and pulse streams, thus rendering a very large number of flow control increments and the corresponding controlled ASM force magnitudes with a relatively small number of valves and waveforms. For example, a set of only six asynchronous waveforms or "clocks", plus a pair of constant "on" and "off" control signals, can be combined by means of only three valves into 512 different force control settings. Similarly, four valves with only six asynchronous waveforms, or three valves with fourteen waveforms, could yield 4095 force control increments, etc.

An APSC is called: *nonredundant* when its pulse stream generates a different force with each distinct combination of the actuating unit and waveform numbers; *consecutive* when higher waveform and/or unit numbers are always associated with a greater force; and *continuous* when nonredundant force control levels are uniqely identified by a sequence of integers.

When the force magnitude decisions are received from a control center in form of a binary output and when x digits are assigned to each one of u APSC actuating units, the total number of controlled force levels N and the number of common source waveforms n must satisfy equations (06) and (07) called *addressing compatibility standards*. Any continuous, nonredundant and consecutive APSC, whose N, n, u and x parameters are selected to satisfy both criteria, will have waveform selections as well as their destinations automatically encoded in the force level signal number.

$$N = 2^{xu} \tag{06}$$

$$n = 2^{x} - 2 \tag{07}$$

For example, in a three-actuating-unit / fourteen-waveform APSC featuring a total of 4096 different controllable force levels, the controller selects an ASM force level 1992. The force control command contains both the selections of the required waveforms and the numbers of actuating units that are their respective destinations. As shown in Fig.13, a fourteen waveform APSC is compatible with hexadecimal coding of the waveforms and the 1992-nd force level is executed simply by sending the 8-th waveform to valve 1, the 12-th waveform to valve 2 and the 7-th waveform to valve 3. All this can now take place instantly through a hard-wired logic without any further control decision processing requirements. Any classical actuating control hardware without inherent neuromuscular behaviour would, in a similar application, require a secondary processor to implement the decisions received from the host computer. Fig.13 also contains a table which illustrates a number of typical APSC design selections that comply with the above addressing compatibility standards.

SUMMARY AND DISCUSSION

The above brief description of a proposed approach to defining and subsequent designing of biorobotic machines calls for emulation of the spontaneous interaction between three groups of variables representing control functions, actuating dynamics and the resulting torque and motion development process. When a live limb acts against an external load, the torque and motion development process is fully described by an array of *actuating profiles*, i.e., joint torque-angular velocity-displacement functions $T[\omega(\theta)]$ associated with all implicated revolute joints of the limb. For a given type and magnitude of external load, the instantaneous torques within these actuating profiles depend on the entire history of control stimuli transmitted to all limb muscles and on all individual active and passive muscle properties. When combined viscoelastic responses of the ligaments and articular capsules of each synovial joint are represented by one "dummy", zero-contractile-element muscle, they can be simply entered into ordinary *Functional Network of Biorobotic Variables* and other modelling procedures to be fully accounted for. Any biorobotic manipulator, with joint actuators that can reproduce at least the basic live actuating dynamics of the corresponding principal joint muscles, will generate, obviously, the lifelike actuating profiles under any kind of external load whenever the control signals emulate their respective live stimuli. In geometric terms, an actuating profile is, generally, a single nonplanar curve in T-ω-θ space and it can be transformed into the parametric form, $T(t)$; $\omega(t)$ & $\theta(t)$, through the relationship $d\theta = \omega dt$. This is of interest in the analysis of isometric activities when only torques without joint rotation are developed.

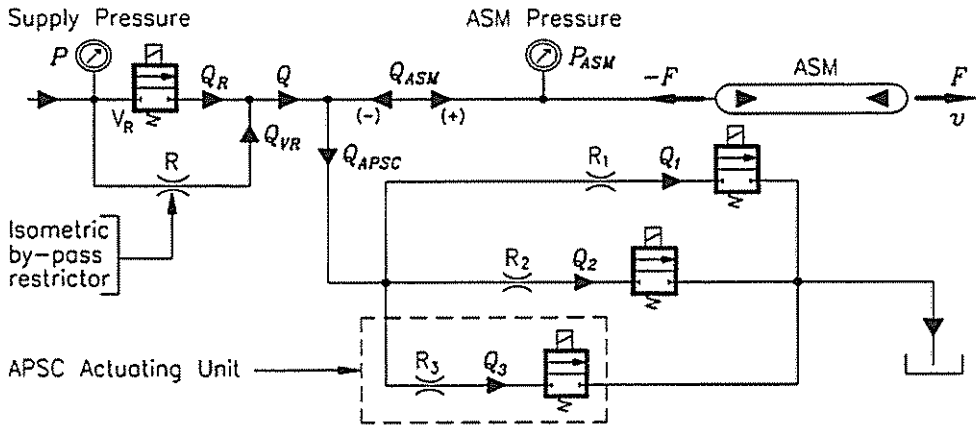
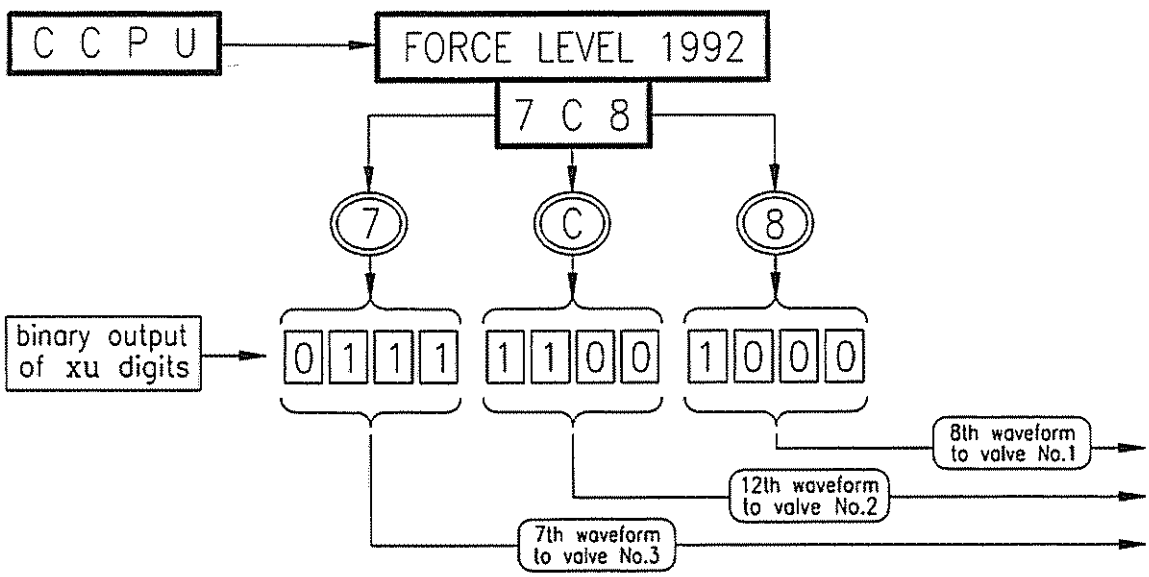


Figure 12: Basic Asynchronous Pulse Stream Control (APSC) circuit.

ADDRESSING COMPATIBILITY STANDARDS : a) $N = 2^{xu}$ b) $n = 2^{x} - 2$

N = number of force control steps x = number of digits assigned to each actuating unit
n = number of waveforms u = number of APSC actuating units



APSC design				CONTROL SIGNAL EXAMPLE						
u	n	x	N	octal code	hex. code	decimal value	Valve No: 4	3	2	1
2	6	3	64	75	n/a	61			111	101
3	6	3	512	424	n/a	276		100	010	100
4	6	3	4096	5007	n/a	2567	101	000	000	111
2	14	4	256	n/a	A5	165			1010	0101
3	14	4	4096	n/a	962	2402		1001	0110	0010
4	14	4	65536	n/a	8CEF	36079	1000	1100	1110	1111

TYPICAL CONTINUOUS, NONREDUNDANT and CONSECUTIVE APSC DESIGNS which satisfy THE ADDRESSING COMPATIBILITY STANDARDS, have both the waveform selections and their valve destinations automatically encoded in the force level signal numbers.

Figure 13: APSC digital concept with addressing compatibility standards.

An artificial and a live joint are biorobotically compatible if they have similar or, ideally, identical *biorobotic functionals* $\mathcal{B}$ that incorporate all elementary biomechanical models relevant in an actuating process. Fortunately, designers do not have to copy all anatomical and physiological features of a live system in order to mimic its biorobotic functional. It is sufficient to pattern only *four essential biorobotic properties*, by means of any practical mechanical concept. Such mechanisms automatically acquire a lifelike generation of joint power under all dynamic conditions as well as compatible instantaneous amounts of stored energy and compatible instantaneous rates of the storage-release energy transfers within each actuating mechanism.

Biorobotic machines, as defined in this paper, respect nature's own conceptual balance between control functions and actuating dynamics found in any selected musculoskeletal system and, therefore, they enable us to take advantage of some already developed and highly optimized voluntary and reflexive control strategies. This option may be appreciated by those who believe that, in order to fully benefit from those "*comparative* studies of controls and communications within live systems and machines", we ought to start with the machines that are mechanically *comparable*. Robotic bi-pedallism, home maintenance or bricklaying-like works and complex assembly applications, to name a few, can not be successfully implemented with the present machine-tool-like technology of dedicated in-plant production robots with limited compliance and without any true inherent lifelikeness. To simplify emulation of control strategies optimized by the somatic nervous systems, some new types of control hardware may also be helpful. The *Asynchronous Pulse Stream Control* system, proposed for fluid-powered *artificial skeletal muscles,* is an example of a systematic identification of technologically relevant biological principles and their inclusion into the inherent characteristics of a simple mechanical solution. An additional incentive for development of all elements of biorobotic control and actuating hardware resides in the fact that they may be used for many types of machines that are not necessarily anthropomorphic, mobile or even biorobotic. Although the human anatomy is used in this introductory review of proposed biorobotic modelling, other chordate anatomies have been examined, e.g., snakes and dogfish [3][8] whose functional morphology is potentially useful for some industrial applications.

More elaborate theories of muscle contraction are needed to explain the process through microscopic features of various proteins ("cross-bridge" kinetics by A.F. Huxley [9][10]); through molecular activities (Davies [11]); through electrokinematic phenomena (Ingels & Thompson [12]), etc. Although such modelling methods can, ultimately, predict muscle dynamics, - see for example [13], they are primarily intended to provide some critical scientific insights into the ultrastructure, physiology and pathology of active muscle tissues rather than help calculate muscle forces. On the other hand, in order to be useful in industry, engineering models in biorobotics must be idealized representations of natural phenomena simplified to the point of being manageable by a designer. These models should simulate tireless operation of healthy live systems disregarding heat generation, fatigue, oxygen consumption and a myriad of other phenomenologically descriptive biological and environmental elements. However, any proposed method of engineering design analysis of inherently lifelike machines must be flexible and comprehensive enough to accommodate any future findings that significantly affect macroscopic aspects of the behaviour of live systems. Quantitative data on active and passive properties of muscle tissues must be extracted from biomechanical research while the live musculoskeletal geometry may be found in specialized studies of functional anatomy. That data base is being steadily expanded and refined.

In view of the above, the strategy in this research is not irrevocably committed to incorporating any particular mathematical model, coefficient or experimental measurement into either machine specifications or methods proposed for their development. The critical focus of this modelling endeavour is to define essential mechanical properties of lifelike machines by means of visualizable modelling concepts and to enable designers to interface three groups of variables representing a set of muscle activating stimuli, dynamic properties of the joint and the components of external loads. All this has to be done while maintaining the universality of methods devised to write interactive actuation algorithms.

The two most important conclusions at this point are: First, the emulation of live dynamics is feasible only with inherently lifelike machines, and second, the best results in this field can be achieved when complete sets of technologically relevant biological principles are implemented in biorobotic designs. Without these two key rules, we can expect great difficulties trying to get through the technological barrier to truly humanlike, autonomous and interactive automation.

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SYMBOLS AND ABBREVIATIONS

APSC	: Asynchronous pulse stream control.
ASM	: Artificial skeletal muscle.
α	: Revolute joint angular acceleration.
$\mathcal{B}$	: Biorobotic functional.
CASM	: Constant acceleration states model.
CDM	: Compound dynamic model.
CE	: Contractile element.
DCM	: Dynamic control model.
ηS, ηP	: Viscous components of Voight elements within SE and PE.
η_S, η_P	: Damping coefficients of SE and PE viscous elements.
F, F_C, F_P	: Actuator force, contractile element force, parallel elastic element force.
F_{CDM}	: Fictitious CDM actuating force.
FNBV	: Functional network of biorobotic variables.
IDM	: Isotonic dynamic model.
J, J_S, J_P	: Isometric joint stiffness, J contributed by SE, J contributed by PE.
J_D, J_{DS}, J_{DP}	: Dynamic joint stiffness, J_D contributed by SE, J_D contributed by PE.
$J_{D(N)}$	: Nominal dynamic joint stiffness.
$J_{DS(N)}$, $J_{DP(N)}$	: $J_{D(N)}$ contributed by SE, $J_{D(N)}$ contributed by PE.
KM	: Kinematic model.
k_P, k_S	: Instantaneous PE spring rate, Instantaneous SE spring rate.
k_{DP}, k_{DS}	: Instantaneous apparent PE and SE spring rates under dynamic conditions.
k_{SP}, k_{SS}, k_{VP}, k_{VS}	: Instantaneous spring rates of live elastic elements SP, SS, VP & VS.
L	: Joint load moment.
L_O	: Joint load moment at zero joint acceleration.
LFM	: Load function model.
l, l_O, l_C	: Actuator length, l with relaxed parallel elastic element, CE length.
l_{SP}, l_{SS}, l_{VP}, l_{VS}	: Lengths of exponential springs representing elements SP, SS, VP & VS.
$\mathcal{L}$	: Joint torque functional for a viscoelastic load.
MUAP	: Motor Unit Action Potential
N	: Total number of force control levels in an APSC system.
n	: Number of asynchronous control pulse waveforms in an APSC system.
ω, ω_{JS}, ω_{JP}	: Joint angular velocity, ω of SE deformations, ω of PE deformations.
PDM	: Parametric dynamic model.
PE	: Parallel elastic element.
Q_i	: Rate of flow through the i-th APSC activating unit.
R, R_i, R_{CDM}	: Moment arm, moment arm of i-th joint actuator, CDM moment arm.
S, S_i, S_{CDM}	: Control stimulus, stimulus of i-th actuator, CDM stimulus.
SE	: Series elastic element.
SS, SP	: Exponential series springs within SE and PE.
T, T_0, T_S, T_P	: Joint torque, isometric torque, torque due to SE, torque due to PE.
T_{S0}	: Static torque required to produce SE related displacement θ_{JS}.
t, t_L	: Time, external load time clock.
θ, θ_o	: Joint displacement, θ for T_P=0.
u	: Number of actuating units in an APSC system.
VS, VP	: Exponential Voight element springs within SE and PE.
v, v_C, v_S	: Muscle or ASM contracting velocity, velocity of CE, velocity of SE.
v_{VS}, v_{SS} etc.	: Contracting velocities of dynamic model elements VS, SS etc.
x	: Number of force level binary output digits assigned to each one of u actuating units in an APSC system.