A SLIDING FRICTION MECHANISM THAT MIMICS SKELETAL MUSCLE FOR DYNAMIC AGILE ANIMAL ROBOTS

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This paper describes a new approach to solving the problem of animal robot actuation. Currently, there are 3 types of humanoid robot, which are (i) "stiff bent leg shuffle robots" that use inappropriate closed loop position and velocity servomechanisms, (ii) "shakey robots" that use compliant actuator robots with a spring in series with the actuator and (iii) "the best yet robots" that use electric motor series spring elastic closed loop force servomechanisms such as Boston Dynamics' Mini Spot Dog robot and the mini Atlas humanoid robot. However, the best yet robots still are not able to run since the motors must reverse at high speed which is inefficient. This paper describes a mechatronics solution to the problem. The solution produces a highly backdrivable actuator similar to our own skeletal muscles.

Keywords: Biomimetic muscle, passive back drivable artificial muscle, ultra low output impedance force actuator, unidirectional impulse force servomechanism, energy-efficient artificial muscle, mechatronic artificial muscle.

ABSTRACT

The need for a biomimetic muscle is described then is followed by a review of state of the art biomimetic muscles, including their advantages and disadvantages and why these actuators are proving to be of limited use as biomimetic muscles. A new species of biomimetic artificial muscle that is suitable as a biomimetic muscle is then described. This new species accurately emulates skeletal muscle in terms of performance, summarised as energy efficiency, back drivability, controllability, power-to-weight ratio, power-to-volume ratio and force resolution. This new species of biomimetic muscle is a mechatronic "sliding friction mechanism" (SFM), which produces a unidirectional force via sliding friction that will enable a new genre of dynamic agile animal robots that can sprint, jump, fly and swim fast. Since the SFM produces a unidirectional force then a pair of SFM's is required to bidirectionally actuate a single limb. The SFM is designed to be equally as effective in (i) static position holding (as in a displacement servomechanism) and (ii) motion articulation (as in a velocity servomechanism) of robot limbs. A proof of concept prototype has been built and successfully tested and a more advanced, more powerful prototype is under construction. The device creates a force impulse which can be programmed as a force-time signature. The device possesses ultra low bidirectional output impedance, i.e. extremely high forward and backward drivability and this back drivability is obtained, uniquely, using a passive method. The term, "output impedance" is defined in the main text. A force actuator with the property of low bidirectional output impedance obtained passively is the primary characteristic for mimicking biological skeletal muscle. Finally, the SFM proof of concept apparatus is described together with a basic control methodology.

THE NEED FOR A BIOMIMETIC MUSCLE

The reader is asked to wonder how are very own muscles work. How do animals and humans walk, run, jump, fly and swim with such accuracy, fluidity, elegance, poise and ease? Currently, Man is not able to create robots that can run like Usain Bolt, dance like Ginger Rodgers and Fred Astaire, do an overhead scissor kick like Wayne Rooney, swerve and chase like a Cheetah, swim and leap from the water like a dolphin or take off, swoop, soar, hover, perch and pluck a fish from a lake like an eagle. Instead, what we have at present are stiff, clumsy, jerky robots such as the Asimo robot with bent knees or the less inelegant but power hungry robots from Boston Dynamics. These robots are very impressive but still there is a problem with their physical performance. Why is this so? What is frustrating this new science of Dynamic Agile Animal Robots? Is it the state of the art in sensors?...in computers?...in software algorithms?....in batteries? No, the answer is none of these.

Instead, the problem lies in the inadequate state of the art of actuators that articulate the limbs. If engineers have a range of actuators from the size of an insect wing muscle up to the size of a race horse's hind leg muscle that emulates biological skeletal muscle then the exciting new genre of Dynamic Agile Animal robots will be entirely possible, and with it, a fascinating new challenge, previously untapped, of the associated Control Methodology of managing individual biomimetic muscles and synergistically-acting groups of biomimetic muscles. Daniel Wohlpert outlines a fascinating theory, [1] of the brain evolving to primarily control muscles. Creating an effective biomimetic muscle will enable scientists and engineers to mimic the brain's control of muscles and thus give greater understanding of this phenomenon since it is difficult to "read" the algorithms in the brain. Furthermore the energetics of animals will be much better understood by scientists and engineers if we can recreate dynamic agile animal robots because it is difficult if not near impossible to accurately measure muscle energies and powers during the active behavior of animals.

Dynamic Agile Animal Robots will create a new industry and, with it, new jobs and opportunities. Interestingly, Hollywood films, such as "I-Robot", illustrate how humanoid robots, being one branch of Dynamic Agile Animal Robots, will be used effectively in society. In the background will be significant job-creating supporting industries concerned with servicing and maintenance together with business opportunities that we can hardly imagine.

REVIEW OF BIOMIMETIC ARTIFICIAL MUSCLES

One of the the most exciting recent development in biomimetic muscles has been carried out by a team led by Sangbae Kim who is Director of the MIT Biomimetic Robotics Lab..His work and that of his collaborators can be seen at [2], [3] which is concerned with the design and construction of a dynamic agile Cheetah robot. It is very interesting to see how this team developed their biomimetic muscles for the robot. They used large diameter, caseless, direct drive brushless DC motors and obtained exceptional results but still not good enough to make the Cheetah gallop more than 22kph. This speed has only been bettered by Boston Dynamics hydraulically actuated Cheetah robot, [4] that has obtained 45kph but this speed is still well short of a Cheetah's 100kphBoston Dynamics has also developed other impressive robots such as Petman and Big Dog, which all use hydraulically driven actuators. More recently is the amazing Mini Spot Dog Robot. Now let us analyse why actuators are not performing well enough to articulate dynamic agile animal robots with the grace agility, speed and precision of their biological counterparts.

Currently existing actuators use a range of physical phenomena to provide force such as (in approximate order of popularity of use), (i) electromagnetic force, i.e. electric motors, (ii) hydraulic cylinder force and (iii) pneumatic cylinder force. Other, less common actuators acting as artificial robot muscles are; (iv) piezoelectric, (v) shape memory alloy, (vi) electric charge force, (vii) electrically activated polymers (EAP's) and (viii) thermal,e.g. bimetallic strip. There are also other methods for providing artificial muscle actuation ranging from twisted string Spanish windlass type to methods based on carbon nanotubes and myogenics, [5]. These less common actuators generally cannot provide sufficient force or performance to match skeletal muscle or are inadequately developed and are thus deemed inadequate (by this author) for use as artificial muscles. So the only viable contenders are actuators that use electric motors or piston/cylinder combinations actuated by liquid or gas. We will see shortly that even these contenders, i.e. the electric motor, pneumatic and hydraulic actuators, fall short of being able to satisfy the criteria for biomimetic muscles and as a result a new species, the Sliding Friction Mechanism, SFM, figure 1, has been evolved to satisfy the criteria.

Aerovironment has pushed the limits of biomimetic muscle design with their highly impressive robot hummingbird, [6]. This is notable because an electric motor and ingenious gear system is used to flap the wings and phase the wing attack angles. However, such a system would lack versatility in its application meaning that is designed only for controlled hovering flight. Such an electromechanical system is unlikely to serve as a generic biomimetic muscle in other animal robots.

Barrett Technology has invented a very interesting actuating technique for robots, [7]. A direct drive DC brushless electric motor is used to drive a low friction cable pulley system that articulates robot arms. The cable system serves as a reduction gearbox transmission system. Since it is an extremely efficient transmission, coupled with a low friction electric motor, the back drivability seems low but this is deceiving since the inertia seen at the end-effector will be significant thus rendering the design unsuitable for biomimetic muscles. This reasoning will be explained shortly but is due to low energy efficiency during, for example, running and flapping.

MIT has invented the Series Spring Elastic actuator, MIT SEA, [8], which appears to be used in many of dynamic agile robots around the world. This biomimetic muscle solves, simply, elegantly and ingeniously, compactly and with low mass, the next most significant requirement of biomimetic muscles which is high back drivability, low output impedance, with an active system. However, the highly significant requirement of high energy efficiency during fast oscillation of robot limbs is not solved since the whole gear train and electric motor armature masses, together with their friction, is dragged along with the oscillating limb.

REASONS FOR THE INADEQUATE PERFORMANCE OF EXISTING BIOMIMETIC MUSCLES

In summary, inadequacies of currently existing actuators concern their inability to mimic accurately biological skeletal muscle. Even Marc Raibert, founder of Boston Dynamics, expresses his concern as quoted below over the state of actuators in his Big Dog robot, [9]. Biological skeletal muscle tissue has the following 11 key properties, (i) high force-to-weight ratio, (ii) fast reaction time (less than 0.1 sec response time to

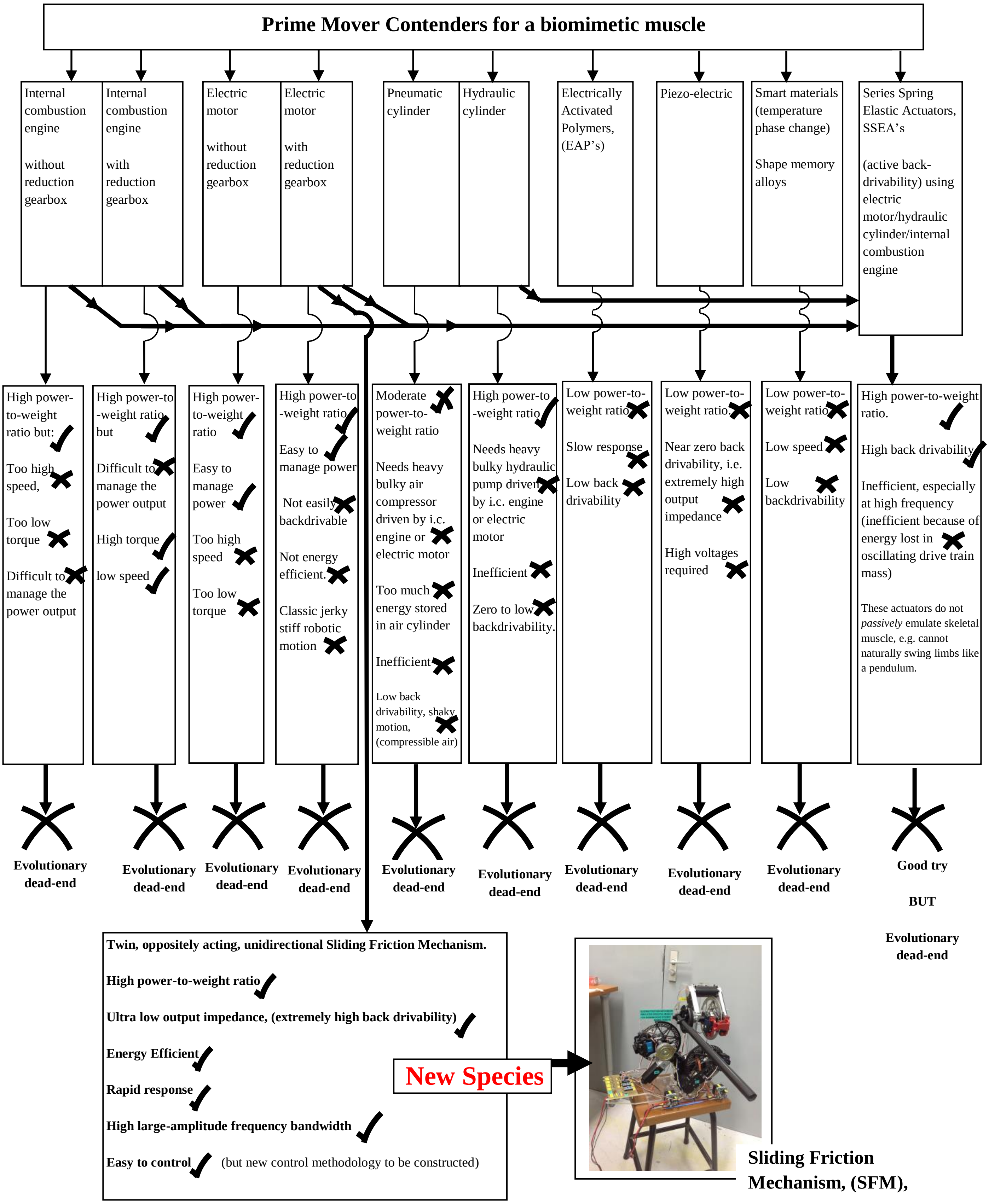

Fig 1. Sliding Friction Mechanism, (SFM), Evolutionary Tree diagram.

The **SFM** accurately emulates the **S**liding **F**ilament **M**odel of biological skeletal muscle.

The **SFM** is a new species of artificial muscle maximum force) that in alliance with (i) produces high mechanical power-to-weight ratio, (iii) low physical volume, (iv) low strain energy stored in the muscle fibres, implying high stiffness output shaft supplying the force, (v) significant latent energy stored in the muscle for approximately 1 minute in order to permit initial explosive output of power such as an Olympic sprinter or a four legged Cheetah, (vi) almost soundless in operation, (vii) self centering, meaning that the muscle, when relaxed will tend to attain a length half way between fully contracted and fully stretched, (viii) high force resolution, (ix) low reflected inertia seen by the limb, (x) negligible forward and back drivable force, otherwise known as high back drivability or low output impedance, which will be mathematically defined later, (xi) ease of controllability (which generally favours electric motors and microcomputer systems).

It should be noted that when the power-to-weight ratio of actuators is assessed then the weight of the whole system including energy production and/or its storage should be taken into account and not just the actuator alone because the actuator should be considered as actuating a stand-alone mobile robot or autonomous machine system, e.g. an animal robot. For example, the weight of a pneumatic or hydraulic actuator should include the petrol/battery plus the internal combustion engine/electric motor plus the compressor/pump and the weight of control components such as pneumatic/hydraulic valves, electric circuits, computers, wires, pipes and in the case of hybrid systems, such components as electric generators.

State of the art actuators for use in robots follow the design methodology of (i) using closed loop position and velocity servomechanisms that give high stiffness and high accuracy and (ii) the trajectory of robot limbs are found using mathematical techniques such as Jacobian matrices. Whereas this can be highly suitable for most engineered systems, e.g. CNC machine tools, it is not considered the way biological systems, i.e. animals, articulate their limbs. Animals use their high back drivability, low output impedance muscles to provide force impulses to their limbs thus resulting in an energy efficient system. In contrary to state of art robot servomechanisms, the position and velocity of these limbs may not be fed back into closed loop servomechanisms. Instead, the force impulse applied to the limb is accurately delivered, probably from an open loop, but nonetheless accurate, force producing muscle. The force-time signature is a relationship that is the result of an in-built program and/or is a learnt process. The open loop position or velocity control of limbs, nonetheless, produces an accurate position-time and or velocity-time signature as can be seen with any animal walking or running. Herein lies the fundamental difference between traditional taught control theory based on closed loop feedback of position, velocity or acceleration of motion system and that of biological brain-muscle systems that provide a force-time signature (an impulse, (N-s)) from an actuator possessing high back drivability that is obtained passively.

Negligible forward and backward drivable force relates to, (i) a limb such as a human arm being able to become limp and easily moved when its muscles are not activated and (ii) the limb being able to be moved against the muscle when the muscle is activated. Most of the aforementioned currently existing actuators cannot be easily forward driven or backward driven with the exception of a direct drive, brushless electric motor that is energized by a current-controlled electrical circuit. However, such a system, whilst being forward and backward drivable, will fail the test of possessing low inertia and high force/high mechanical power-to-weight ratio hence a direct drive electric motor is also inadequate as a biomimicking artificial muscle.

The reason for this is that electric motors possess adequate mechanical power-to-weight ratio for artificial muscles but in the wrong format meaning that electric motors produce high power only at high speed with low torque rather than low speed and high torque, the latter being suitable for biomimetic muscles. Hence electric motors require the speed to be reduced and the torque increased using a high reduction gearbox with a reduction ratio typically in the order of 300:1. A gearbox introduces (i) friction and (ii) added inertia due to the inertia of moving gears and motor armature magnified by the square of the gear ratio. Thus a gearbox will decrease the forward and backward drivability giving high bidirectional output impedance which is undesirable because it results in large energy losses as a limb is oscillated. An electric motor using Neodymium Boron Iron magnets together with a planetary or harmonic drive gearbox results in a prime mover that possesses both high power-to-weight ratio and high power-to-volume ratio; both ratios of which are highly suitable for biomimetic muscles but the motor/gearbox combination gives undesirable high output impedance due to increased gearbox friction and extremely high reflected inertia which amounts to almost 10,000 times the inertia of the electric motor rotating armature, (300:1 gearbox ratio squared).

So the conclusion is that currently existing electric motor/gearbox combination actuators directly connected to robot limbs are unsuitable as biomimetic muscles.

Now we come to examining pneumatic and hydraulic systems. Both types use a piston and cylinder or swash plate motors but the pneumatic type can also use a bag that as it fills with air it becomes fatter and shorter similar to the apparent shape change of a real muscle. (Skeletal muscle does not get fatter but instead becomes more erect as it is energised). Both pneumatic and hydraulic types suffer from lack of forward and backward drivability due to piston friction and valve flow losses.. Both types require on-board compressors or pumps and a bank of fluid control valves that are heavy bulky and not as easy to control as an electric motor system and neither can they respond with the rapidity of an electric motor system. .

So the conclusion is that pneumatic and hydraulic system actuators are unsuitable as biomimetic muscles.

This is a critical situation; there appears to be no actuation methodology that is suitable for emulating biological skeletal muscle. This seems to be the conclusion arrived at by other inventors such as the MIT Series Spring Elastic Actuator (SEA) inventors and that is why they developed their force feedback system as a way out of the trap which is; we need the gearbox in an electric motor system but it is also our worst enemy. The MIT SEA solves the problem actively with a mechanical spring at the force-providing output shaft. The problem is that it does not solve the problem of energy efficiency. This is solved with the Sliding Friction Mechanism, SFM.

However, before the SFM is described, some theory and definitions will be outlined.

THEORY AND DEFINITIONS

The SFM device described here can be considered an impulse servomechanism producing an impulse as follows:

$$\text{Impulse, } I = \int_{t_1}^{t_2} F.dt \text{ (N-s)} \qquad \text{eq. (1)}$$

Where I is the impulse (N-s), F is a fixed or variable force (N) applied to a mass M(kg) from time, t_1(s) to time t_2(s).

An impulse, I, applied to a mass, changes its momentum, p, according to eq.(2):

$$\text{Momentum change, } \Delta p = I \qquad \text{eq. (2)}$$

Momentum, p = M x v, where v(m/s) is the velocity of a mass, M. For simplicity, we can assume that a constant force, F, acts on a constant mass, M, for time Δt. Thus an impulse is produced that results in a change in velocity, Δv, of the mass where, in this case, the change in velocity is proportional to the impulse, I, eq.3.

$$\text{Change in velocity of mass, } \Delta v = \frac{F}{M}.dt = \frac{I}{M} \quad \text{eq.(3)}$$

Since robots are largely composed of rotary joints and limbs with polar 2nd moments of inertia, J, then a similar analysis means that a limb acted on by a torque, T, has its angular velocity, ω, changed by an amount proportional to the rotational impulse, $I_{rot} = \int T.dt$ (N-m-s) applied to it.

This means that, if we know the required change in velocity of the mass, and, we have a device that can apply a precise impulse with respect to time, then, we can control the velocity of the mass with respect to time. The sliding friction mechanism, SFM, does just that without interfering with the free motion of the limb that the mechanism is actuating, thus enabling dynamic robots. In contrast, limbs driven by an electric motor-gearbox combination can never be freed from the friction and mass effects of the electric motor and gearbox; the limb is forever dragging with it, the mass and friction of the attached actuator. For example, a running humanoid robot has legs that oscillate forward then backward at 2.5Hz. This means that a traditional bidirectional electric motor and gearbox will accelerate its moving mass (armature plus gears) to its maximum velocity forward then decelerate to its maximum velocity backwards at 2.5 times every second. This is enormously wasteful of energy and unnecessary if you have a pair of oppositely acting, clutched, unidirectional electric motor gearboxes, which is the working methodology of the sliding friction mechanism, SFM.

It needs to be borne in mind that muscles are also required to apply an impulse to a limb or set of limbs even when there is zero velocity change. This case refers to the muscles applying impulses that overcome the force due to gravity acting on the limbs when a body is standing still. The analysis of a multi jointed robot is more complicated than expressed above since an impulse applied at the arm applies an equal and opposite impulse to the rest of the body and ultimately to the ground if the robot is standing on the ground. Thus limb impulses are reflected through the body. Nonetheless the basic principles remain as above. Almost without exception, state of the art robots are articulated by closed loop angular/linear displacement servomechanisms or angular/linear velocity servomechanisms. Rarely, if at all, are robots articulated by impulse servomechanisms. Probably the MIT SEA is the exception.

This sliding friction mechanism is based on the premise that skeletal muscles are not to be seen as displacement or velocity servomechanisms but rather seen as impulse servomechanisms that position the limb in the correct displacement or with the correct velocity or acceleration. The implication of an impulse force-producing actuator is that the force produced should be independent of the limb position, velocity and acceleration. We define this property as high forward and backward drivability. We will call this phenomenon, ultra low, negligible or near-zero bidirectional output impedance. The meaning of "impedance" is the resistance to an applied quantity. Here the applied quantities are, (i) displacement, (ii) velocity and (iii) acceleration and the resistance will be the change of force to each of these applied quantities. The output impedance will be quantified as the ratio of the change in force to these applied quantities. The meaning of "output" is that the applied quantities are applied external to the artificial muscle via the output shaft that is connected to the limb. Low bidirectional output impedance is defined as low values of all of the following three output impedance coefficients, k_{displ}, k_{vel}, k_{accel}, with the actuator programmed to exert a demanded force, F_{dem}. However, F_{muscle} is the actual force produced by the muscle which will be a different value from F_{dem} due to friction and inertial effects. Ideally, for perfect forward and backward drivability, and zero bidirectional output impedance, F_{muscle} is always equal to F_{dem}. In practice, we aim F_{muscle} and F_{dem} to be as near equal as possible with a passive system in contrast to an active system such as the MIT SEA. We now set about quantifying low output impedance as follows:

1. $F_{muscle} = F_{dem} + k_{displ}.x$

   where F_{dem} is the force demanded by a muscle controller
   F_{muscle} is the actual force produced by the muscle
   k_{displ} is displacement output impedance, N/m or N-m/rad
   and x is displacement (m) or (rad)
   Zero or negligible displacement impedance will be produced when, $k_{displ} \approx 0$, which means that force, F_{muscle}, is independent of actuator displacement. Thus there should be no springiness in the actuator output shaft.

2. $F_{muscle} = F_{dem} + k_{veln}.(dx/dt)^n$
   where k_{veln} is the velocity output impedance and consists of (i) friction output impedance (N) or (N-m) for n=0 and (ii)viscous output impedance, (N/(m/s)) or (N-m/(rad/s)) for n=1 and (iii) fluid dynamic output impedance $(N/(m/s)^2)$ or $(N\text{-}m/(rad/s)^2)$ for n=2
   and dx/dt is actuator velocity (m/s) or (rad/s).
   Zero or negligible velocity output impedance will be produced when, $k_{veln} \approx 0$, which means that force, F_{muscle}, is independent of actuator velocity. Thus there should be no coulomb, viscous or fluid dynamic losses in the actuator output shaft.

3. $F_{muscle} = F_{dem} + k_{accel}.d^2x/dt^2$
   where k_{accel} is acceleration output impedance, $(N/(m/s^2)=kg)$ or $(N\text{-}m/(rad/s^2)=kg\text{-}m^2)$
   and d^2x/dt^2 is actuator acceleration (m/s^2) or (rad/s^2).
   Zero or negligible acceleration output impedance will be produced when,
   $k_{accel} \approx 0$, which means that force, F_{muscle}, is independent of actuator acceleration. Thus the moving elements of the output shaft should be as lightweight as possible to produce as little inertia force as possible.

To help the reader's intuitive understanding of the meaning of zero bidirectional output impedance we can imagine getting hold of the actuator and pushing and pulling against it. The result will be that the force felt from the actuator remains constant, equal to $F_{muscle} = F_{dem}$, whatever is the actuator bidirectional displacement, bidirectional velocity or bidirectional acceleration. In other words the biomimetic muscle will possess negligible bidirectional output impedance. Another important property of a biomimetic muscle is that of force resolution meaning that the force exerted by the muscle should be resolute to, for example 0.1% of its maximum force, e.g. 1N force resolution for a 1000N maximum force biomimetic muscle.

The sliding friction mechanism, SFM is also modeled on biological skeletal muscle in that such muscle tissue cannot exert pushing forces but can only exert pulling forces due to contraction. In other words skeletal muscles can only contract; they cannot extend. Biological muscles are thus inherently unidirectional. This unidirectionality is not slavishly copied just because Nature has evolved the muscle this way. The fundamental advantage in being unidirectional over that of a bidirectional system is that there is no energy loss in reversing the direction of the muscle system. The cost of a unidirectional system is that a pair of unidirectional systems is required to achieve bidirectionality.

Since skeletal muscles cannot extend themselves, they are in fact extended due to its partner muscle contracting on the opposite side of the limb. Skeletal muscles thus work in pairs and are known as *agonistic* and *antagonistic* muscles. Each skeletal muscle is capable of being agonistic or antagonistic depending on whether the limb is being flexed or extended. The agonistic muscle is the one overcoming the load exerted on the limb and the agonistic muscle is the one relaxing itself to allow its partner to contract against the external load.

It is highly instructive to examine the working principle of skeletal muscle because it directs the mind towards a biomimetic muscle design solution.

WORKING PRINCIPLE OF BIOLOGICAL SKELETAL MUSCLE

The following account is based on references at [10], [11], [12], [13], [14] and is the author's interpretation of information and events given by these references. In other words the author has taken some creative licence and liberties with the information but at the same time has made effort to remain as accurate and factual as possible.

Muscles are manufactured from five compounds which are:

1. *Myosin* which forms the very axially stiff *thick filament*
2. *Actin* which is the main constituent of the very axially stiff *thin filament*
3. *Tropomyosin* which is used in the *thin filament*
4. *Troponin* which is also used in the *thin filament*
5. *Titin* also known as *Connectin* which is a rope-like, sometimes elastic, (sometimes elastic followed by relatively inextensible behaviour at the end of its travel), long chain molecule that connects the thick and thin filaments together at their sarcomere centres.

The muscle building blocks will now be built up in sequence. We will start with the articulated myosin unit, figure 2. The articulated myosin unit consists of a single myosin filament with a 2 degree-of-freedom (2dof) articulated walking mechanism at each end of the filament. The unit is symmetric about a central axis, figure 2.

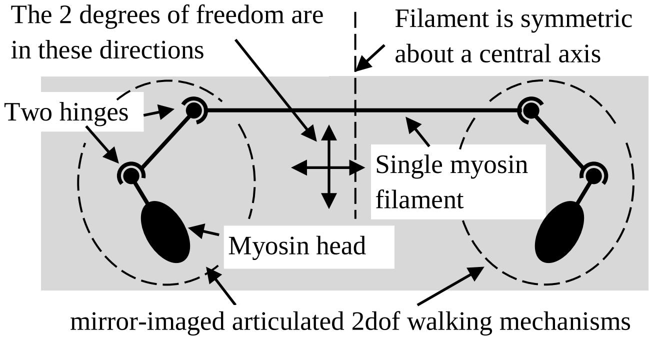

Figure 2. Articulated myosin unit with a 2 degree of freedom articulated walking mechanism at each end of a myosin filament

Each 2dof articulated walking mechanism "walks" similar to a foot connected to a leg. However, the walking mechanisms walk in opposite directions in a mirror-image as if walking away from each other, figure 3.

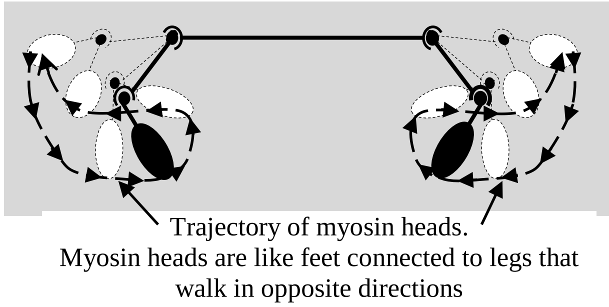

Figure 3. Path of the opposing walking 2dof mechanisms at each end of the myosin filament

But the walking myosin heads are not allowed to walk anywhere because (i) they are connected together and (ii) they are walking in opposite directions. Instead they do the only alternative option which is, so as to speak, to make the floor move under their feet meaning that the thin filaments are pulled, or contracted, together. These thin filaments are largely composed of actin but have an amazingly ingenious electrical-chemical-mechanical mechanism that utilizes tropomyosin and troponin to create force. These thin filaments, fig 4, are pulled together as the myosin heads walk and thus form the basis of a contractile mechanism.

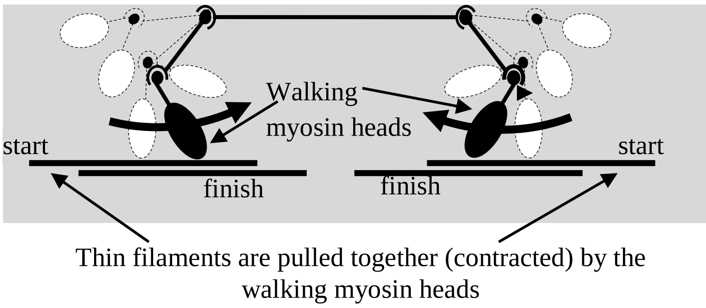

Fig 4. The walking myosin heads apply force to pull the two thin filaments closer together thus forming a contractile mechanism. Note that the myosin heads slip on the surface of the filaments

An important point to realise is that the myosin heads can still walk and produce contractile force even though the thin filaments are inhibited from movement. In other words the myosin heads apparently <u>slip but still apply force.</u> It will be shown shortly that continuous force is possible despite the myosin heads periodically releasing their grip during their circulatory 2dof motion because there are many walking myosin heads acting at random times.

The walking mechanisms only "walk" when energized by nerves from the brain and they walk at a speed in proportion to the nervous excitation. As already stated the nervous excitation of muscle tissue is ingenious and involves electro -chemical – physical - mechanical mechanisms. However it is only necessary to describe the mechanical properties here. When there is no nervous excitation the myosin heads cease to walk and retract, like an aeroplane undercarriage, away clear from the thin filaments, figure 5.

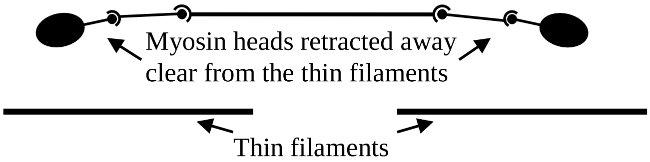

Figure 5. The myosin heads can retract away clear from the thin filaments.

This complete physical disassociation between the myosin heads and the thin filaments is a key feature of muscle tissue. It means that skeletal muscle tissue can allow, if necessary, free unhindered motion of limbs meaning there is no feeling of friction or little feeling of inertial mass connected to the limp limb. This is one of the key features of obtaining low output impedance and high back drivability.

The method by which the myosin heads pull on the thin filaments appears not to be known accurately. The literature uses the phrase, "the myosin heads *bind* with the thin filaments". Precisely what is meant by, *bind*, is not clear. For example, is it a frictional force or an electric charge force or do the myosin heads slot into grooves in the thin filaments? Whatever is the precise mechanism, the Sliding Friction Mechanism utilises friction to emulate the *binding* mechanism.

Figures 2 to 5 above already show the basic micro-mechanism of skeletal muscle. The next step is to assemble, en-masse, many of these micro-mechanisms to form a complete muscle. To do this, natural biology stacks together many articulated myosin units of various lengths into a bundle to form what is called a myosin "thick filament", figure 6.

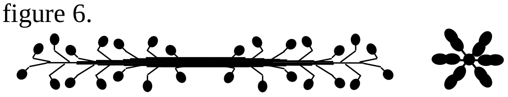

Figure 6. Side view and end view of thick filament consisting of a bundle of numerous 2dof articulated myosin units of various lengths.

The author considers that the core (not the heads) axial stiffness of these myosin bundles is very stiff. The right hand side of figure 6 also shows the thick filament viewed from the end, where it can be seen that the myosin units are arranged into a hexagon format. This is because the thick filaments can form a 3-dimensional nested hexagonal honeycomb arrangement that matches with the thin filaments that are arranged also in a hexagonal arrangement, figure 7.

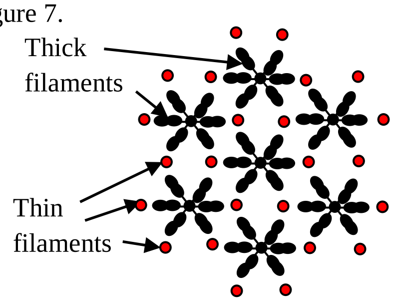

Figure 7. Cross-sectional view muscle showing thick and thin filaments packed in a hexagonal arrangement

Figure 8 shows three sets of thin filament "wire cups" with their myosin bundles and titin ropes removed.

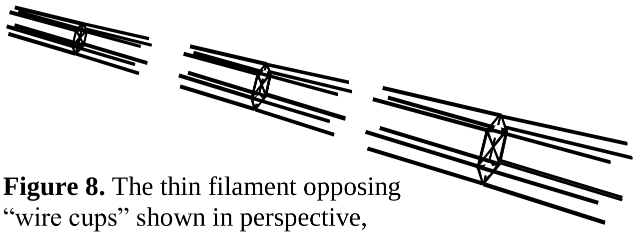

Figure 8. The thin filament opposing "wire cups" shown in perspective, (not tapered).

Likewise, as with the high axial stiffness of the thick filament myosin bundle, the author also considers that the axial stiffness of the thin filament actin wires is also highly stiff.

One thick filament bundle and a pair of opposing thin filament wire cups form the basis of a single muscle contractile unit called a *sarcomere*, figure 9 and figure 10.

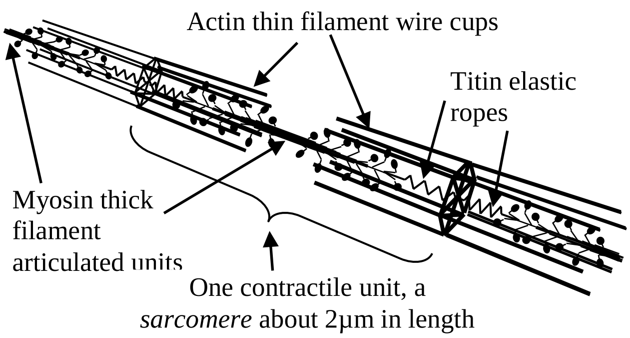

Figure 9. Sarcomeres are single contractile units. Here they are joined together. Note the constituent parts: the actin thin filament wire cups, the myosin thick filament articulated units and the titin elastic ropes

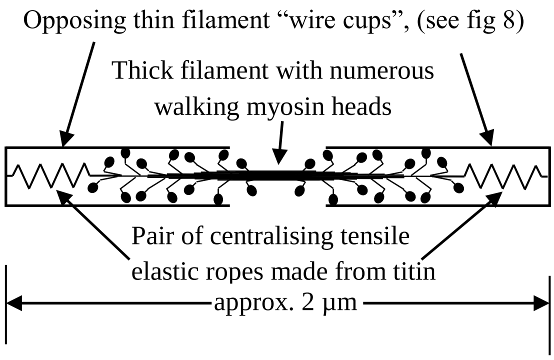

Figure 10. Basic muscle contractile unit, the *sarcomere.*

Figure 9 also shows a short length of sarcomeres joined together. Sarcomere size varies according to muscle application but for humans they are approximately 2μm in length so a bicep muscle of 200mm in length will consist of approximately 100,000 sarcomeres strung together in a continuous line. There will of course be many more strings of sarcomeres all mutually connected in parallel.

It is easier to explain further action of skeletal muscle by reverting back to a 2-dimensional arrangement in order to simplify explanation of the muscle contractile principle.

Figure 10 shows the basic muscle contractile unit, known as a *sarcomere* which is of the order of 2μm in length. The sarcomere is composed of three items which are (i) the already described, thick filament with numerous walking myosin heads, (ii) the already mentioned thin filaments but this time shown as a pair of opposing "wire cups", (see figure 8) and (iii) a further component in the muscle system which is a pair of centralizing tensile ropes made from titin. These two ropes are mounted at each end of the thick myosin filament.

Mechanically speaking, the probable purpose of these ropes is two-fold; one is to keep the thick filament centralised with respect to the thin filament cups and the second is to stop the muscle being pulled apart. The titin also appears to possess springiness that is non-linear in the respect that its restoring force is low except until it reaches the end of its travel. Thus it can be that it acts more like an *uncoiling tethered rope*. No doubt Nature has evolved the titin to be a linear spring in some muscles such as bird wing flapping muscles. Since the thick filament can be considered stiff, it can be understood that the titin spring acts in parallel thus forming an external resonant system as shown later in figures 22 to 25. External resonant system means that the mass-spring system exists separately and disconnected from the force excitation system. It also implies importantly that there is no series spring which is how some European researchers see the composition of biomimetic muscle.

We are now in the position of explaining the contractile action. We start with the sarcomere in its fully extended state, figure 11, which occurs, for example, in the bicep arm muscle when the arm is straightened by contracting the opposing tricep muscle. It is to be remembered that the articulated myosin heads can only walk one way which is to drag the thin filaments together, not apart. The sarcomere in its fully extended state results in a large gap between the thin filament wire cups. The gap is known as the *H-zone*.

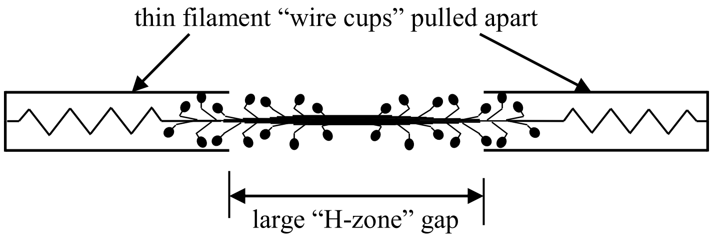

Figure 11. Sarcomere shown fully extended showing large gap between the thin filament wire

If, now, the articulated myosin heads are activated then the thin filament wire cups are pulled together, figure 12, and the H-zone now decreases to a small size. The sarcomere can extend and contract +/- 15% from its mid-range length of 2μm.

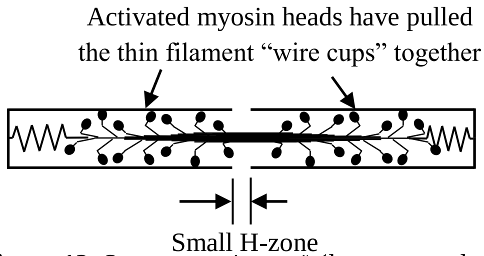

Figure 12. Sarcomere shown fully contracted

The sarcomere muscle unit has a very special property which is that it can apply a contractile force, F, which is largely independent of the position, x, velocity of contraction, dx/dt, and due to its low mass is largely unaffected by the acceleration of contraction, d^2x/dt^2, figure 13.

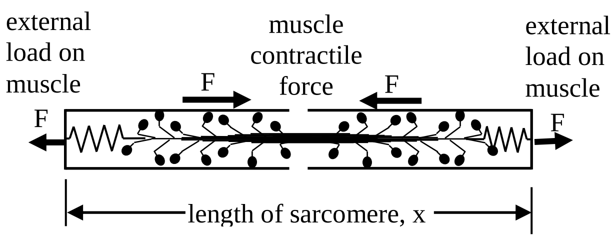

Figure 13. Contractile force, F, is largely independent of x, dx/dt and d^2x/dt^2.

Figure 13 shows the sarcomere resisting an external tensile load of, F, by exerting an equal and opposite contractile force of, F. The special property means that the sarcomere will allow the relative free sliding, in both left and right directions, of the wire cup thin filaments over the thick filament myosin heads whilst still exerting a constant force, F. This means that skeletal muscle tissue is forward and backward driveable and thus is essentially a force producing device. The implication is that the myosin heads “slip” over the thin filaments whilst still applying a contractile force.

It can be seen that the workings of biological muscles are very interesting and a fundamental departure from engineered systems that are position and/or velocity and/or acceleration producing actuators. Yes, engineered systems do apply a force to achieve a position and/or velocity and/or acceleration and yes paradoxically, biological muscles do control the position and/or velocity of limbs but the difference between the two actuating methods is manifested by the forward and backward drivability of skeletal muscle tissue.

There are relatively high forward and backward drivable actuators on the market at present such as those by Barrett Technology. The drawback of these actuators is either too much reflected mass seen at the end-effector. Skeletal muscle tissue in contrast is low in mass so engineers still largely have not solved the problem of creating an artificial muscle that closely mimics skeletal muscle. The two exceptions seem to be (i) the MIT series spring elastic actuator, SEA and (ii) the sliding friction mechanism, the SFM.

We will now wind up the discussion on the workings of biological skeletal muscle at the sarcomere level by just saying that a complete muscle is orderly assembled from many sarcomeres placed in parallel and series, figure 14. Adding sarcomeres in parallel will increase contractile force whilst adding in series will increase the change in length. Thus the work capability of a muscle is proportional to its volume.

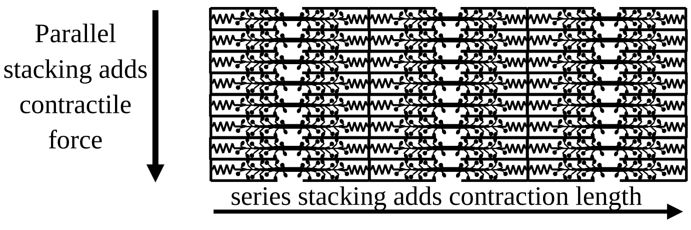

Figure 14. Sarcomeres are stacked in series and parallel. Playing with the parallel and series stacking causes effective impulse matching of different length limbs and different length moment arms. This is an interesting area to research.

The next step in developing our discussion of the effectiveness of the sliding friction mechanism, SFM, is to explain how force-producing contractile muscles work in pairs to articulate limbs. We first make a simplification in the representation of the contractile muscle by showing it as a sliding telescopic system with a force-producing contractile element which applies a variable and controllable force that is exerted to contract the telescopic system, figure 15.

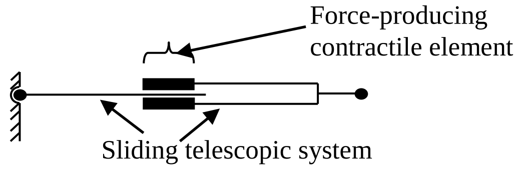

Fig 15. Simplified muscle in fully extended position

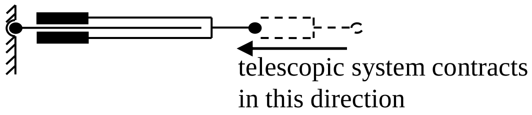

Fig 16. Artificial muscle in fully contracted position

Figure 15, and figure 16 above, show the muscle in its fully extended position and in its fully contracted position respectively.

It is interesting to note that the simplified representation of the muscle, figure 15, can be realized as a linear electromagnetic telescopic device. It can be designed to be accurately forward and backward driveable so why it is not being used? The answer is that the mechanical power-to-weight ratio is too low. As already stated, achieving high mechanical power output from an electromagnetic device requires a small electric motor running at high speed delivering mechanical power through a reduction gearbox.

As already stated, muscles cannot apply an extending force; they can only apply a contractile force. Thus the only way for a muscle to extend is by the muscle contracting on the other side of the limb. The following figures make this clearer. Figure 17 shows a human forearm and upper arm in its mid-range position. If the forearm is brought closer to the upper arm then the joint is said to be “flexed”, figure 18.

Since skeletal muscles can only apply a contractile force, the only muscle that can flex the forearm is the bicep muscle which is also known as the flexor muscle. The tricep muscle, on the other hand relaxes its contractile element which allows the forearm to flex and, in turn, the tricep muscle becomes extended.

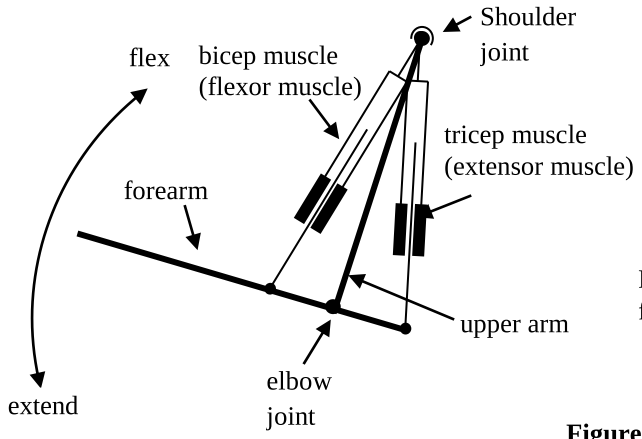

Figure 17. Human forearm and upper arm shown in mid-range position with bicep and tricep muscles that flex and extend the forearm

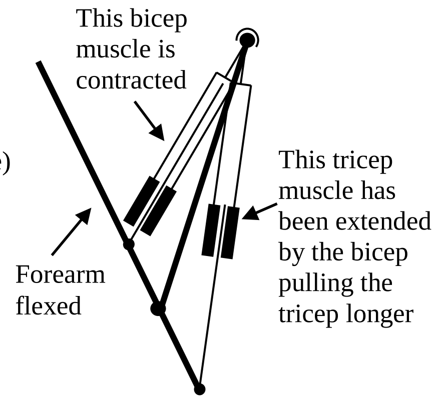

Figure 18. Forearm shown in a flexed position due to the bicep muscle contraction

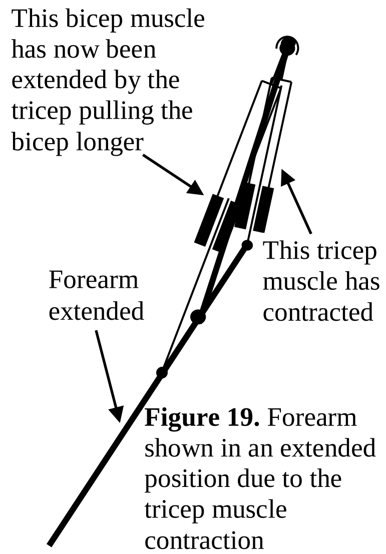

Figure 19. Forearm shown in an extended position due to the tricep muscle contraction

If the arm is straightened then the joint is said to be "extended", figure 19. This time the bicep muscle relaxes and the tricep muscle, (the extensor muscle), is contracted to extend the forearm. Thus, this time the bicep muscle extends. The arm is typical of most skeletal muscles in the body and typifies skeletal muscles existing in pairs, i.e. one muscle is used to flex a limb and the other is used to extend the limb thus exhibiting bidirectional motion.

Three more terms will now be introduced; they are "reciprocal inhibition", "agonistic muscle" and "antagonistic muscle", all three of which will now be explained via an example in the next few paragraphs.

You would expect that when the forearm flexes, only the bicep will contract but this is not true. First of all when the brain commands the forearm to flex, both bicep and tricep muscles are activated but of course there can be no movement until the tricep relaxes and allows the bicep to overpower the bicep. What happens is that the flexing bicep muscle sends a signal to its opposing mate to allow flexing to occur by reducing the contractile force in the tricep muscle. The process is known as "reciprocal inhibition". The inhibition of the tricep muscle is greatest at the start of flexing and the least at the end of motion. In other words, the contractile force of the tricep is lowest at the beginning of flexing and greatest at the end of motion. The bicep works inversely by being the most strongly activated at the beginning of motion and decreasing near the end of motion. The effect can be considered analogous to velocity feedback that is used in engineered control systems.

The bicep, which is overpowering the tricep muscle to create flexing, is called the "agonistic" muscle because it is the muscle undergoing the greater stress or agony (Greek, agon = struggle). On the other hand, the tricep muscle, which is moderating the forearm motion to ensure it does not slam into the upper arm and cause damage, is called the "antagonistic" muscle (= "the one that fights against").

If now the forearm is extended, the roles of the bicep and tricep muscles are reversed. In this case the more highly activated tricep muscle becomes the agonistic muscle because it has to overpower, using reciprocal inhibition, the bicep muscle which now becomes the antagonistic muscle.

We now conclude the description of biological skeletal muscle and turn our attention to engineering a man-made solution to a biomicking skeletal muscle which is the main subject of this chapter. First we formulate a mechanical model of skeletal muscle.

MODELLING SKELETAL MUSCLE

Researchers have created a mechabical model of skeletal muscle [15]. The model, known as the Hill/Huxley model is shown in figure 20.

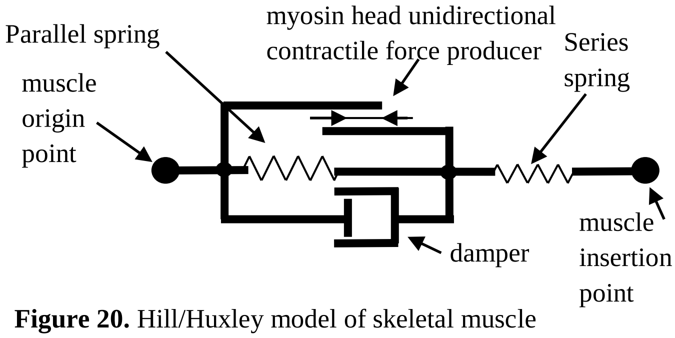

Figure 20. Hill/Huxley model of skeletal muscle
Note that all thick black lines are considered infinitely stiff

The author considers that the model can be better represented if the series spring and the damper are not present. The reasons relate to (i) the difficulty in controlling a muscle system if the series spring is present and (ii) the low energy efficiency if the damper is present. The author considers that the antagonistic muscle is used to damp motion via reciprocal inhibition which is a well known physiological phenomenon.

Hence the author proposes the simplified model of figure 21.

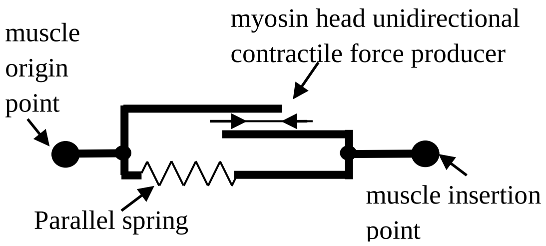

Figure 21. Simplified model of skeletal muscle

It can be considered that Nature plays with the parallel spring stiffness rate depending on its application. For example the rate is low in humans allowing freedom of movement but would be a high rate in an avian breast muscle resulting in a high efficiency oscillating tuned mass-spring system for its flapping wings. We now move on to implement the model, figure 21, in a mechatronic system, the sliding friction mechanism, SFM.

DESCRIPTION OF THE SLIDING FRICTION MECHANISM, SFM,

The SFM biomimetic muscle has evolved by choosing to mimic biological skeletal muscle tissue by creating a force via clamping a pair of friction pads onto a unidirectional continuously running surface such as a brake disc, figure 22.

The force produced is from sliding frictional force between the continuously rotating surface and the friction pads. The millions and maybe billions of minutely sized protuberant sliding friction areas that are in sliding contact with the running surface and the friction pads can be considered to mimic the millions and maybe billions of sliding filament myosin walking heads that exist in skeletal muscle. Both the minutely sized friction areas and the minutely sized myosin heads produce nano Newton-second randomly applied force impulses that when summed together produce a smooth, low noise, high value force for each second that they are in operation. Friction pads such as automotive or bicycle disc brake pads are chosen because they (i) are capable of exerting very large braking forces, (ii) are small and lightweight, (iii) are low cost and (iv) capable of long life. We will assume a constant friction coefficient, independent of the slip speed, between the rotating surface and friction pads equal to the coefficient of kinetic friction. We use the kinetic friction coefficient by arranging the unidirectional running surface to always run faster than the pad speed. The heating energy loss is minimized by ensuring the slip speed is kept as low as possible. The rotating surface runs in one direction only, i.e. it is unidirectional; it does not change direction. However, it can change its surface speed.

The force, which represents the muscle contractile force, is extracted from lightweight friction pads that are freely allowed to move about the rotating disc axis thus providing a force independent of position, velocity and acceleration of the friction pads. The continuously rotating surface provides the source from which is tapped the force. The force from the friction pads is continuously variable from zero up to the maximum force available from the continuously rotating surface.

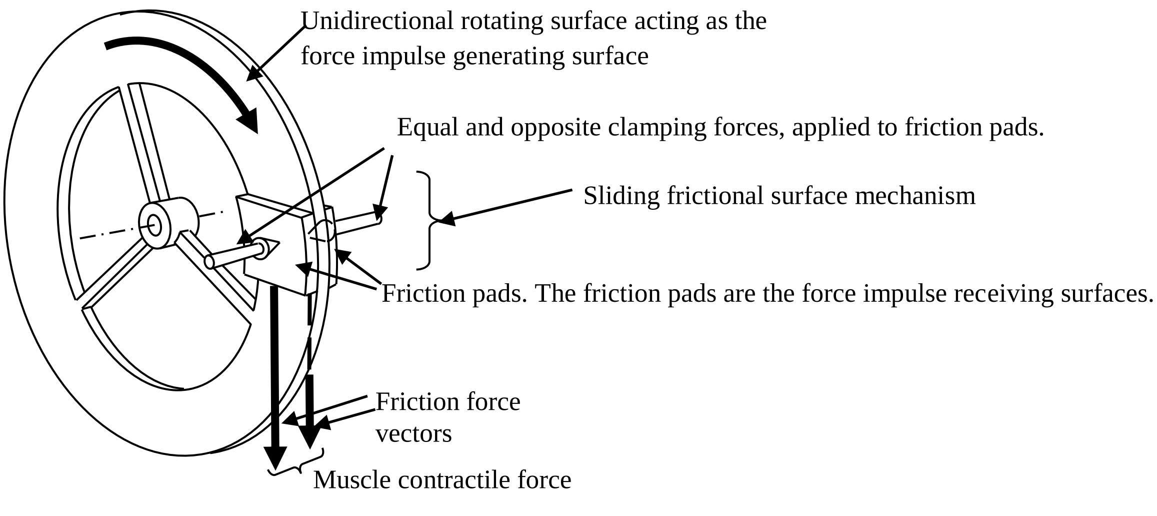

Figure 22. Principle of muscle contractile force generation from clamped friction pads that mimics the myosin heads interacting with actin thin filaments

The force is varied by varying the pad clamping force. Since the rotating surface is unidirectional, the friction pad force will also be unidirectional and thus will mimic skeletal muscle. The clamping force can be reduced to zero such that there is no contact between the friction pads and rotating surface thus mimicking the myosin heads being completely retracted, figure 5.

The speed of the continuously rotating surface is arranged to be greater, or marginally greater than, the maximum speed of the friction pads which are connected to a telescopic slider. Thus there will always be slip occurring between the friction pads and the rotating surface. If there is always slip then the contractile friction force provided by the friction pads is dependent on a constant friction coefficient which is the coefficient of kinetic friction. Hence the contractile friction pad force will be directly proportional to the clamping force. Thus the contractile friction pad force which represents the muscle contractile force can be accurately controlled by accurately controlling the friction pad clamping force. Slip, occurring between the friction pads and the rotating surface, means there will be energy wasted that is manifested as heat dissipated between the friction pads and the rotating surface. A control system is to used to limit the amount of slip to a minimum in order to minimise energy loss. Biological muscles also have this slipping energy loss that manifests itself as muscles getting hot even if the limb is not moving but supporting a weight; anyone practising Yoga or Pilates will know this well. This energy loss appears to be a natural law of inevitable payment in return for obtaining the property of ultra low output impedance that is created passively.

The Sliding Friction Mechanism solves the problem associated with energy wastage by reversing the rotation direction of the electric motor/gearbox together with solving the problem of achieving low oscillating mass. First of all the electric motor/gearbox is kept rotating in one direction only and secondly the high inertia of the motor/gearbox is not seen by the moving limb or the moving parts of the muscle. In fact the relatively high kinetic energy of the motor/gearbox is an advantage because it reduces the fluctuations in the speed of the rotating surface as the friction pads extract periodic impulses from it. The moving mass, which is connected to the limb, is low because it is equal to the mass of the friction pad clamping system which can be made a low value.

It is also to be noted with the SFM that it together with alternative embodiments shown later in this chapter, are capable of absorbing shock loads without damaging the motor. This is due to the maximum clamping force applied to the friction pads being purposefully limited such that the maximum contractile force remains safely less than the force that will do damage to the motor gearbox teeth or the rotating surface.

The Sliding Friction Mechanism does not suffer from the need of the motor/gearbox having to reverse direction but does bear the apparent disadvantage of requiring a pair of artificial muscles to actuate one limb. In fact herein lays the dualism which is; <u>either</u> two separate unidirectional muscles to actuate one limb <u>or</u> one bidirectional muscle to actuate one limb. The apparent disadvantage of requiring two unidirectional artificial muscles is that the weight and cost will be higher than one bidirectional muscle. This disadvantage has to be overcome by future research and development.

As regards cost; the SFM will spur the development of a manufacturing process that should make a pair of unidirectional actuators that is no more expensive than one bidirectional actuator. Anyway if a device solves a difficult problem then cost is not of immediate importance. It should also be made clear that the unidirectional muscles of the SFM operate interdependently which means that both muscles can be activated at the same time such that one reciprocally inhibits the force of the other. This means that greater flexibility and limb motion performance can be obtained than one unidirectional system providing bidirectional motion with a reversing gear which means that only one direction can be activated at any one moment. It is important to make a note on the speed of reaction of the device or alternatively the bandwidth of force response. The rapid speed of the unidirectional and bidirectional force response of this device is its key advantageous feature. Furthermore, when a pair of muscles is used to cause oscillation and/or reversal in a robot limb then this device excels over the state of the art. And this is the reason: the speed of response of force is dependent on the speed at which the friction pads are forced against the rotating surface.

The rotating surface is already rotating at speed and does not have to speed up or slow down and reverse; it simply runs in one direction at a certain speed. The friction pads are placed very close to the rotating surface such that with zero force when the pads are not in contact at all, the combined gap on each side of the rotating surface will be of the order of 0.1mm. This gap can be closed very quickly, especially since the pads are small and lightweight, in the order of 1msec with a model aircraft servomechanism, e.g. Futaba BLS172hv which has a maximum torque rating 3N-m. The time to reach a torque of 1N-m is approximately 4msecs. If the Futaba servo exerts a clamping force on the friction pads through a 2mm radius arm, then a clamping force of 500N on either side of the rotating surface can be applied in approximately 5msecs. The friction pads, e.g. automotive brake pads, are very stiff in a direction perpendicular to the clamping direction. Furthermore, so also is the stiffness very high of the rotating surface, e.g. a steel band, in the direction of clamping. Hence the clamping force is increased rapidly as the friction pads are clamped through a small distance and this clamping force of 500N, as already calculated, is exerted in 5msecs. The kinetic friction coefficient of brake pads is approximately 0.25 and so a muscle contractile force of 250N is possible from an opposing pair of friction pads with a rise time of 5msecs. Now that the first embodiment of the device has been described, the reader will have some understanding of its working methodology. So it is now appropriate to describe, with an example, of one of its most important properties which is that concerned with limb oscillating dynamics.

Nature has evolved an ingenious low bidirectional output impedance, unidirectional impulsive force method of skeletal muscle design for enabling animals to oscillate their limbs efficiently at high speed; for example, the legs of a race horse or the legs of a cheetah, or the 25Hz oscillating frequency wings of a hummingbird. We illustrate nature's method in steps with a very simple example which is that of a mass of 0.25kg being oscillated along one axis only, the x-axis, figure 23, which represents the first step.

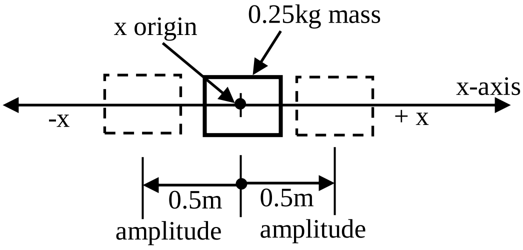

Figure 23. Simplified lumped mass model of an oscillating eagle wing that is flapping up and down (but shown side to side)

Hence average power to be created is (1/2) x ($2/\pi$) x 250 ≈ 80watts

A remaining 80watts of power is to be dissipated as heat.

This is a large power just to oscillate the wing mass and since an eagle has two wings then the bird has to produce an average power of 2 x 80 = 160watts during hovering flight and we have not even considered yet the power required to produce lift! One cannot imagine that nature has evolved such a wasteful system just to flap the wing mass. Hence let us assume that evolution has produced a resonant spring-mass system using elastic tissue in parallel with the muscles such that the eagle flaps it wings at the resonant natural frequency of, ω_n = 20rad/s. The spring stiffness is given from the equation for a resonant system:

So for convenience we use two massless, pre-tensioned tensile springs; each one with a stiffness of 50N/m to obtain a 20rad/s resonant system as in figure 24.

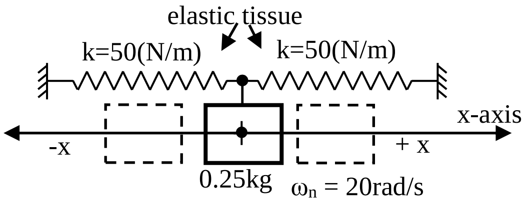

Figure 24. The eagle wing now equipped with elastic tissue thus creating a mechanical system that oscillates almost effortlessly at 20rad/s

In this case the oscillating action will be virtually effortless in overcoming the inertial forces. This makes much more sense because then the only power required is in overcoming the dominant aerodynamic forces that produce lift plus minor friction forces in the wing joints. Notwithstanding the inbuilt spring rate constant of the elastic tissue varying, the eagle just needs to remember that it needs to flap its wings at the resonant frequency and then all will be well. If it flaps outside the resonant frequency, then the bird will tire quickly. In fact, if you watch small birds such as myna birds or starlings, they seem to "switch on" their wings when taking off; the frequency seems not to vary. This makes good economical engineering and evolutionary sense; the design of bird wings is such that all energy goes into lift and thrust and not into inertial energy loss.

Now, it is well known that a high quality resonant system must have low friction and thus possess a low damping ratio. If the force excitation system has friction such as an electric motor with a gearbox or a pneumatic cylinder, then there is little or no possibility of exciting an oscillating wing into resonance since there will be little or no resonant peak. Arguably, the only way to create an excitable high quality resonant system is to isolate the electric motor/gearbox friction (i.e. the exciter) from the mass/spring system and make sure that the mass/spring system has extremely low friction. This is not the end of the story because if the exciter is isolated from the mass/spring system, such as the MIT series spring elastic actuator by Pratt and Williamson, yes you will excite a high Q resonant peak but the power to drive the oscillating motor/gearbox will be excessive. Thus, arguably the only way to create an excitable high Q resonant system and to do it with low power is to use one or two unidirectional exciters (i.e. muscles) with as near perfect forward and backward driveability, see combinations in figure 25, figure 26 and figure 27. Such systems can be executed using the SFM.

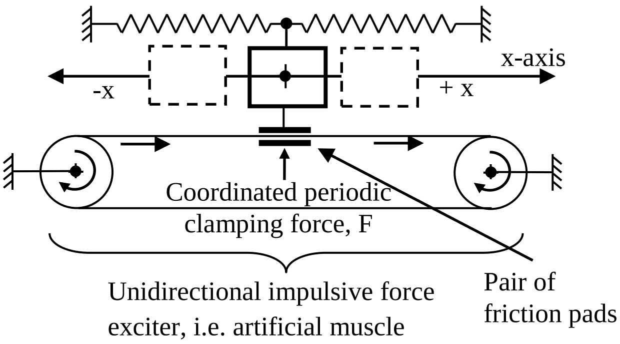

Figure 25. Excitation method 1 for excitation of a resonant system.
Single unidirectional impulsive force excitation using one, single acting, Sliding Friction Mechanism

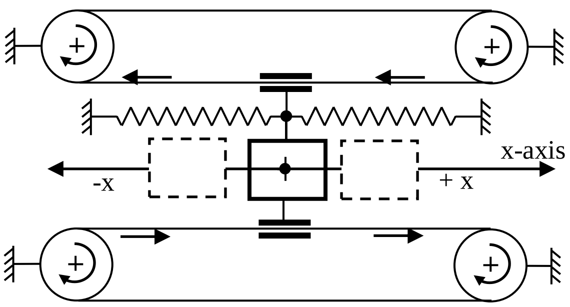

Figure 26. Excitation method 2 for excitation of a resonant system.
Dual, unidirectional, opposite-acting impulsive force excitation using two, single acting, Sliding Friction Mechanisms

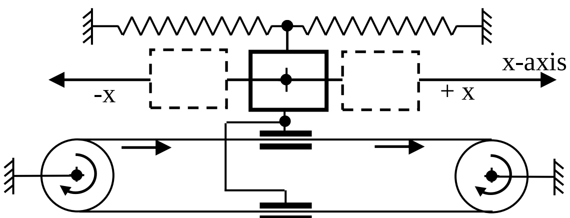

Figure 27. Excitation method 3 for excitation of a resonant system.
Double acting single unidirectional impulsive force excitation using one, double acting, Sliding Friction Mechanism

It can be argued that a spring can be added to a bidirectional exciting system (to the motor/gearbox; not the wing system) such that, it too, can be tuned, albeit without a resonant peak, to the resonant frequency of the wing/tendon system and yes, this is true, but the cost is the high mass of the spring to do this which means it is not an efficient solution. A high mass spring is required because the high reciprocating mass of the motor/gearbox combination means that the spring must store a high amount of strain energy to match the kinetic energy of the reciprocating mass. A spring that stores a higher energy must require a higher mass to do so. Good artificial muscle design should keep all reciprocating masses as low as possible. So we are back to an inevitable solution which is an impulsive, ultra low output impedance unidirectional muscle.

TYPES OF ROTARY EMBODIMENT OF THE SFM

1. Dual, unidirectional, opposite-acting muscle system

A rotary embodiment of the SFM is shown in figure 28. It is designed to produce rectilinear contractile force from a rotating friction pad pair. Rectilinearity is due to a tendon runner which is shaped into an arc whose centre is at the centre of the rotating surface. The embodiment is based on the dual, unidirectional, opposite acting muscle system (method 2, figure 26)

We now arrange an SFM pair in an agonistic-antagonistic arrangement, figure 29. Two mirror-imaged sliding friction mechanisms running in opposite directions flex and extend the limb. Herein we can see a disadvantage of just one artificial muscle acting alone, that of gyroscopic precession of the unidirectional rotating surface plus the motor and gearbox combination as the mobile platform, to which the muscle is attached. However, placing two sliding friction mechanisms back to back with the rotating surfaces rotating in opposite directions but at the same speed means that gyroscopic precession moments will be cancelled out. Figures 30 and 31 show the SFM pair extending and flexing respectively the forearm of a robot limb, e.g. a humanoid robot forearm.

2. Double take-off embodiment

Figure 32 shows an example of double acting single unidirectional impulsive excitation. (Excitation method 3 as in figure 27)

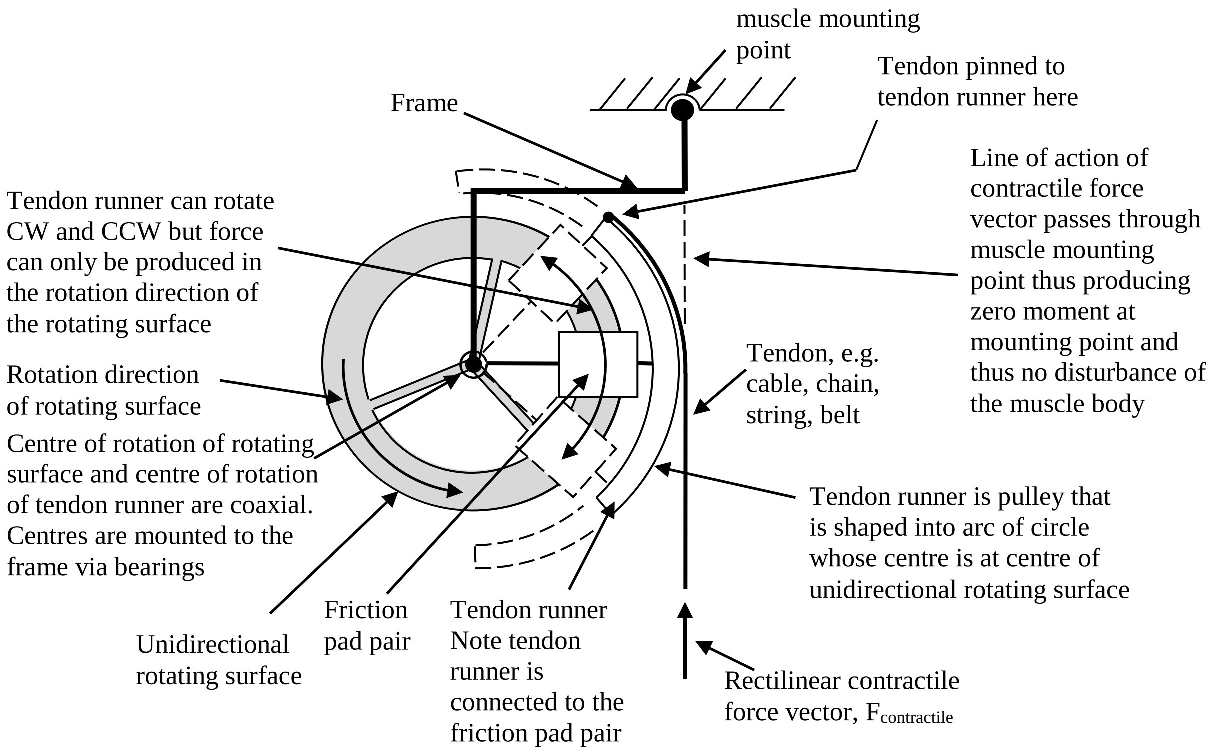

Figure 28. Rotary embodiment producing rectilinear contractile force

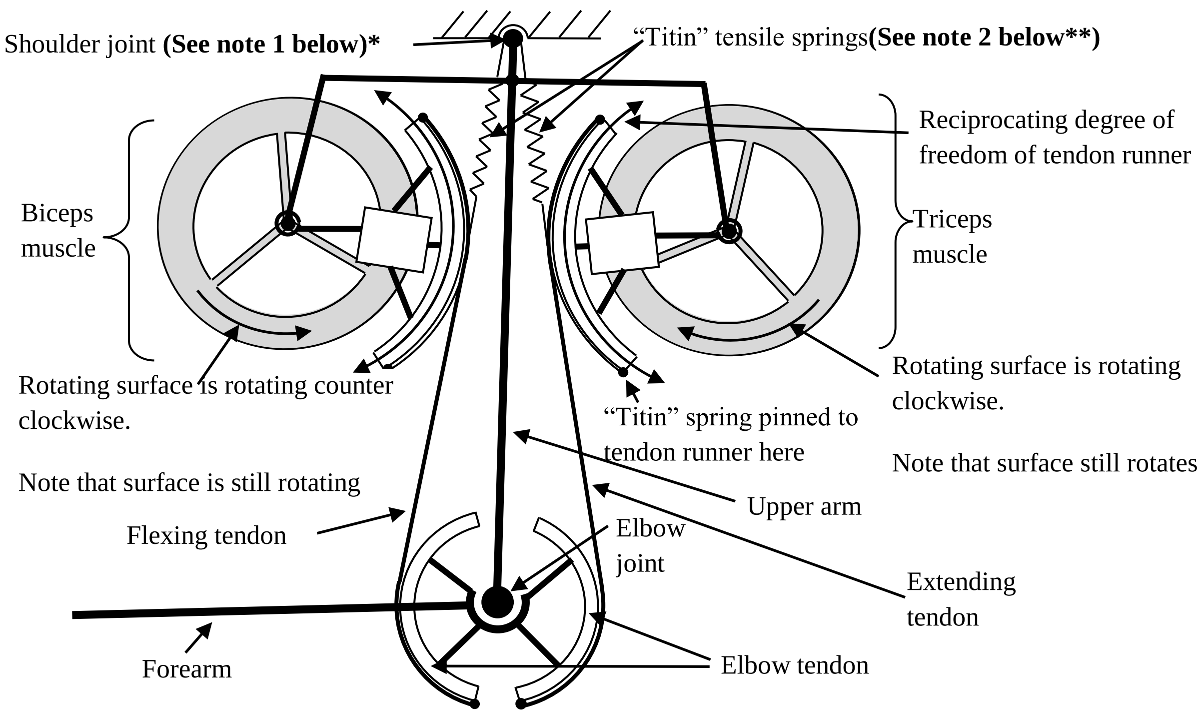

Figure 29. Arrangement using rotary to rectilinear unidirectional sliding friction mechanisms in an agonistic/antagonistic pair arrangement to produce bidirectional motion of a robot limb, e.g. humanoid robot forearm. The muscles are shown oversize for clarity. In practice the muscles will be more compact and resembling the shape of human biceps and triceps muscles. Note that the line of action of each contractile force vector passes through the shoulder joint thus applying no moment of force at the shoulder joint when the muscles are in action.

Notes for figure 29 above

***Note 1**. The two muscles have an "origin" (medical term) at the shoulder joint such that the contractile force line of action passes through the joint. This design in synergy with the elbow tendon runner applies no moments to the upper arm to sustain throughout the range of movement of the forearm. In other words a pure couple is applied at the elbow joint and no other torques or moments are applied to the upper arm. If this were not the case then the muscles actuating the upper arm would require additional corrective energy to correct the undesirable and superfluous moments acting on the upper arm thus resulting in an inefficient muscle system. Of course there will an unavoidable moment applied to the upper arm brought about by any acceleration of the forearm that creates inertial forces that have to be resisted by the upper arm muscles.

**** Note 2**. The "titin" springs have low stiffness spring rate if it is not required to create a resonant spring-mass system. Low rate springs do not serve the purpose of centralising the forearm although in practice there will be a small centralising force. In fact low rate springs serve the purpose of keeping the flexing and extending tendons taut without any significant energy required to flex and extend the forearm limb. High rate springs have a similar effect of keeping the tendons taut but also provide a resonant spring-mass dynamic oscillating system but has the disadvantage of requiring significant energy to displace the forearm limb when the muscles are used to statically position the limb or to velocity profile the limb. Thus adjustable variable rate "titin" springs will permit the muscle system to operate in static, dynamic and velocity profiling modes

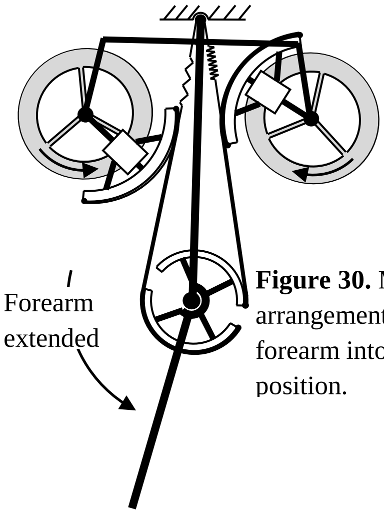

Figure 30. Muscle pair arrangement displacing the forearm into the extended position.

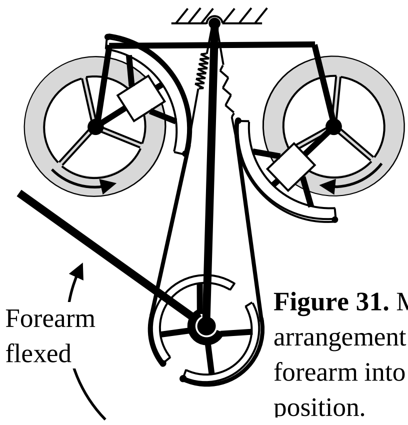

Figure 31. Muscle pair arrangement displacing the forearm into the flexed position.

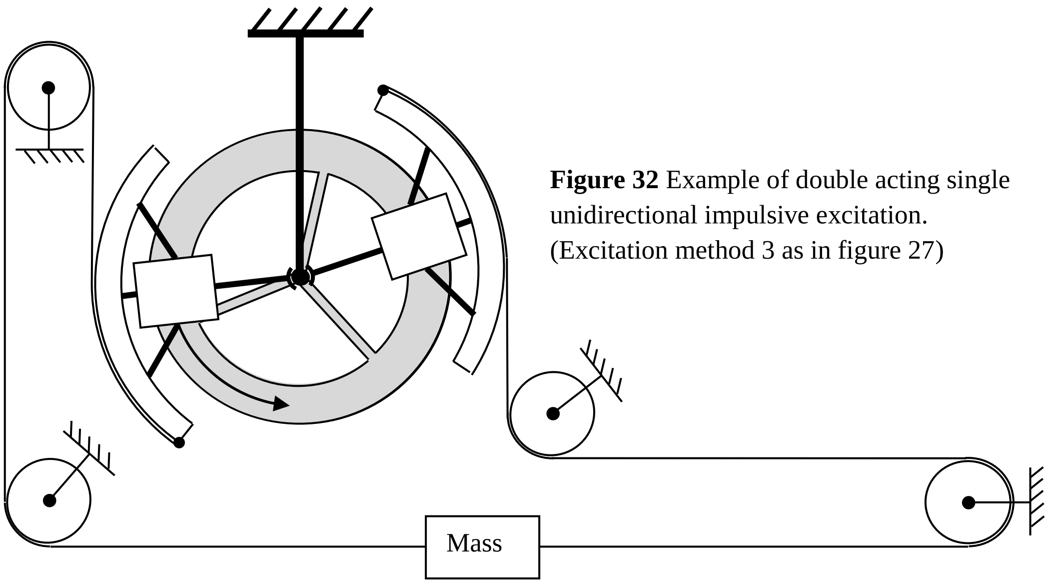

Figure 32 Example of double acting single unidirectional impulsive excitation. (Excitation method 3 as in figure 27)

BASIC CONTROL METHODOLOGY

The control methodology is in its early stages since only a proof of concept SFM has been constructed, figure 33. In the pipeline is a much improved SFM that uses a 2.8kW (mechanical output power) brushless D.C. motor together with a harmonic drive gearbox. This device will have a mass of 3kg and produce a pulling force of 2000N and large angle (+/-60°) full power response at 3Hz.

Currently, the proof of concept bidirectional SFM system has a brief specification as follows:

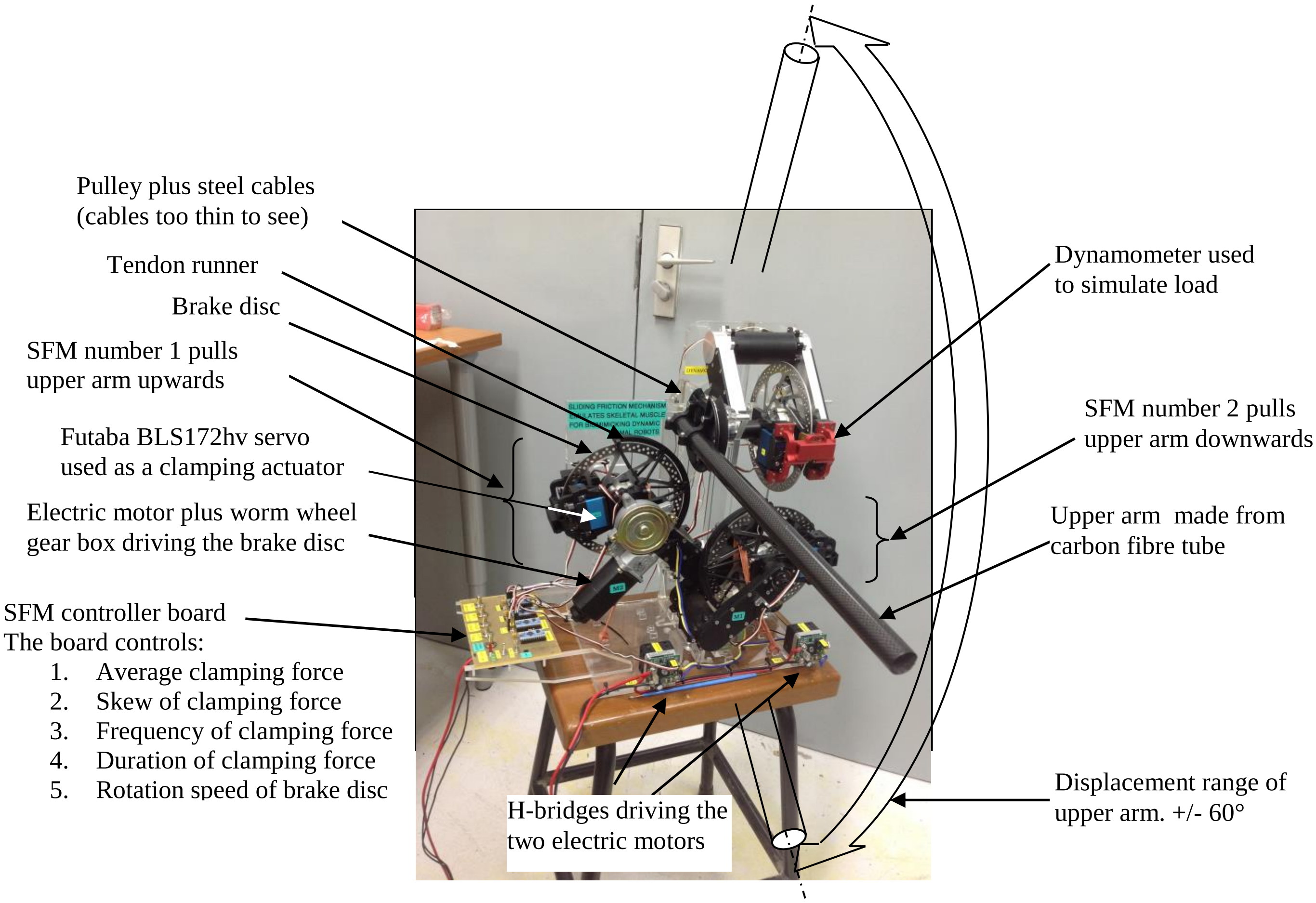

Figure 33 Sliding Friction Mechanism proof of concept apparatus

(i) A twin unidirectional SFM system mounted in an agonistic-antagonistic arrangement similar to figures 28, 29 and 30, that produces bidirectional motion of a carbon-fibre arm via a steel cable and pulley arrangement. The arrangement mimics the pectoralis/supracoracoideus breast muscle set that actuates, down and up respectively, the upper arm of a bird wing.

(ii) Each SFM driven by a brushed D.C. motor and worm-wheel gearbox that drives a 160mm diameter bicycle brake disc, (150mm mean diameter). The motor gearbox has a maximum mechanical power output of 60watts at 120rpm (≈13 rad/sec) thus producing a torque of 4.8N-m at this angular velocity. The torque constant of motor gearbox seen at the gearbox output is 1N-m/A.

(iii) The force is extracted from each SFM via a clamping system that provides clamping force from a pair of oppositely acting Futaba BLS172hv integrated servos. Each servo produces a maximum torque of 3N-m at with a torque constant of 1N-m/A. The clamping force acts via a 20mm long radius arm on a friction pad that is a commercially available component that matches the bicycle brake disc. A clamping force of 150N is achieved with a 3A per servo current, (6A total servo current because there are 2 servos per SFM). Such a clamping force produces a friction force of 75N with a 3A per servo current.

(iv) The SFM force is applied via a tendon runner of 86mm radius that actuates a pulley of radius 43mm via a steel cable. Thus a maximum torque of 43mm x 75N = 3.2N-m can be applied to the carbon fibre upper arm. A current of 3A per servo is not advisable since it will significantly decrease servo life. Hence the proof of concept SFM system is driven with a maximum servo current of 2.1A per servo thus producing a maximum upper arm torque of 2N-m. The maximum angular velocity of the upper arm is thus 13rad/sec x 86mm/43mm ≈ 25rad/sec. Thus the maximum possible angular velocity of the upper arm is 25rad/sec. It is advisable that the upper arm maximum angular velocity is less than 25 rad/sec since that is one basic premise of the SFM that there should always be some slip, albeit minimum, between the brake disc and the tendon runner. Assuming an amplitude of 1rad and assuming the upper arm is oscillated sinusoidally at ω_{arm}, then:

(a) the upper arm angular position, θ_{arm} can be represented as, $\theta_{arm} = 1\sin \omega_{arm}$ t

(b) the upper arm angular velocity, ω_{arm} = ω_{arm}cos20t

(c) the upper arm angular acceleration, $\alpha = -\omega_{arm}^2 \sin \omega_{arm}$ t

The polar 2nd moment of inertia, J_{arm} of the upper arm, including pulley, tendon runner, two Futaba servos and steel cables was calculated as 0.005kg-m^2. The maximum torque available to drive the upper arm is 2N-m. hence, the upper arm angular velocity of oscillation is given by:

$J \times \omega_{arm}^2 = 2$N-m

Thus, ω_{arm} = sqrt(2N-m/0.005kg-m^2) = 20rad/sec (3.2Hz)

An experiment was carried out to oscillate the upper arm at 3.2Hz and amplitude of 1radian. The result was that 3Hz was possible which is encouragingly close to the calculated value of 3.2Hz.

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