EIS*CSA* State-of-the-Art Session - Industry

Muscular dysbalances, fact or fiction:
an engineers point of view.

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The Mechanical Servo System approach:

From a mechanical engineers point of view, human beings may be seen as rather complex mechanical servo systems. With the help of modern body models, this complex system can be disassembled into individual, less complex components. The waste engineering knowledge accumulated over the past 100 years or so may now be applied to model and optimise the properties of these subsystems.

With the application of some basic physical principles, a simple set of design rules can be derived for the basic components the **arthrons**. If we assume, that there is no friction and no external load, the following simple rules apply:

- Acceleration ω' (= $d\omega/dt$) is equal to torque **M** divided by inertia **J** or $\omega' = M/J$ equation 1
- Stroke **s** as function of acceleration ω' and time **t** is equal to: $s = \frac{1}{2}\omega' t^2$ equation 2
- According to Steiner's law, inertia **J** is equal to : $J = m r^2$ equation 3
  with **m** = mass of moving element and **r** = distance of centre of gravity from axis of rotation.

Using above equations and the assumption, that the maximal force, which can be developed by a muscle, is proportional to its cross section, the first set of design rules will be:

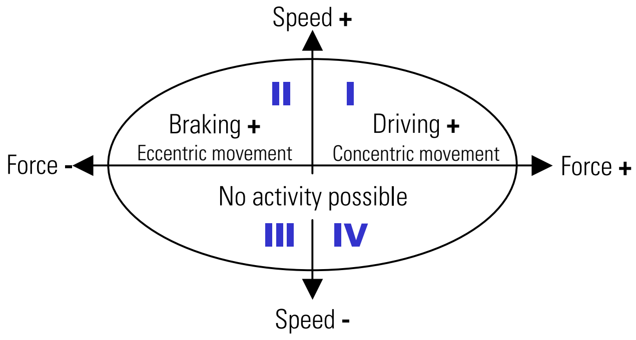
- Move as slow as possible for a given task as the torque (and thus the necessary muscle cross section and muscle weight) will increase with the square of **1/t**, that means that even under the condition, that the drive system (muscle) is located on the stationary side and doesn't move , we need 4 times the cross section and weight to reach the goal in half the time.
- Keep the centre of gravity as close as possible to the axis of rotation, as inertia **J** and thus necessary drive torque **M** for a given acceleration ω' increase with the square of its distance from centre of rotation.
- Keep the moving mass **m** as low as possible, as inertia **J** and thus necessary drive torque **M** for a given acceleration ω' increase linear with **m**.

Biological / technical drive systems:

The arthron in its simplest form can be described as a structure consisting of two rods, linked together by a joint and two drive mechanisms. These drive mechanisms have due to their nature the special property, that they actively can work just in one direction. In servo description language, they would be classified as two-quadrant drives.

The graphical representation of the operating area of such drives is shown to the left.

Two-quadrant drive

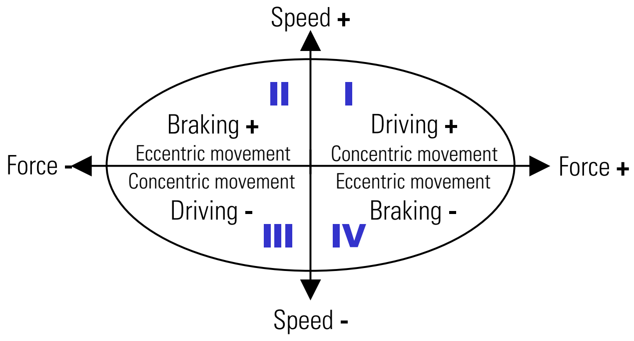


Muscles produce (concentric) mechanical work when contracting (first quadrant) and absorb (eccentric) mechanical energy (second quadrant) while being stretched by external forces. They cannot work in quadrants III and IV.

In technical servo systems, usually actuators like electrical motors or double-acting hydraulic or pneumatic cylinders are used. All of them are normally quite symmetrical in their properties and operate as so called four-quadrant drives, which means that the same drive element can generate (concentric movement) and dissipate (eccentric movement) mechanical energy in both directions.

The graphical representation of the operating area of such drives is shown to the left.

Four-quadrant drive



On first sight, biological drives with their inherent 2-quadrant operation, which always needs a minimum of 2 drive systems for proper operation and stabilisation of a joint seem to have a substantial drawback compared with technical solutions. However, when having a closer look to the consequences, this image changes quite a lot. In equations and rules presented above, only inertia-related forces were considered. Under these conditions (free movement without any external load), fully symmetrical drives would be the optimal solution. As soon as we introduce additional external forces with a joint-specific dominant direction or different speed requirements depending on direction of movement, asymmetry comes into play. The dominant external force influencing the design is gravity. The biggest effect on optimal design will occur on the ankle, the arthron most distal from body centre of gravity, which has to bear the total body mass. On this joint, both factors, the unidirectional external force resulting from gravity (most people seldom hang on their toes) and quite different timing requirements (short touchdown time with high speed movement, long, relatively slow return) coincide. Another good example is the trunk. Here, speeds are always slow and gravity again becomes the key factor for design.

Key benefits of separate two-quadrant drives:

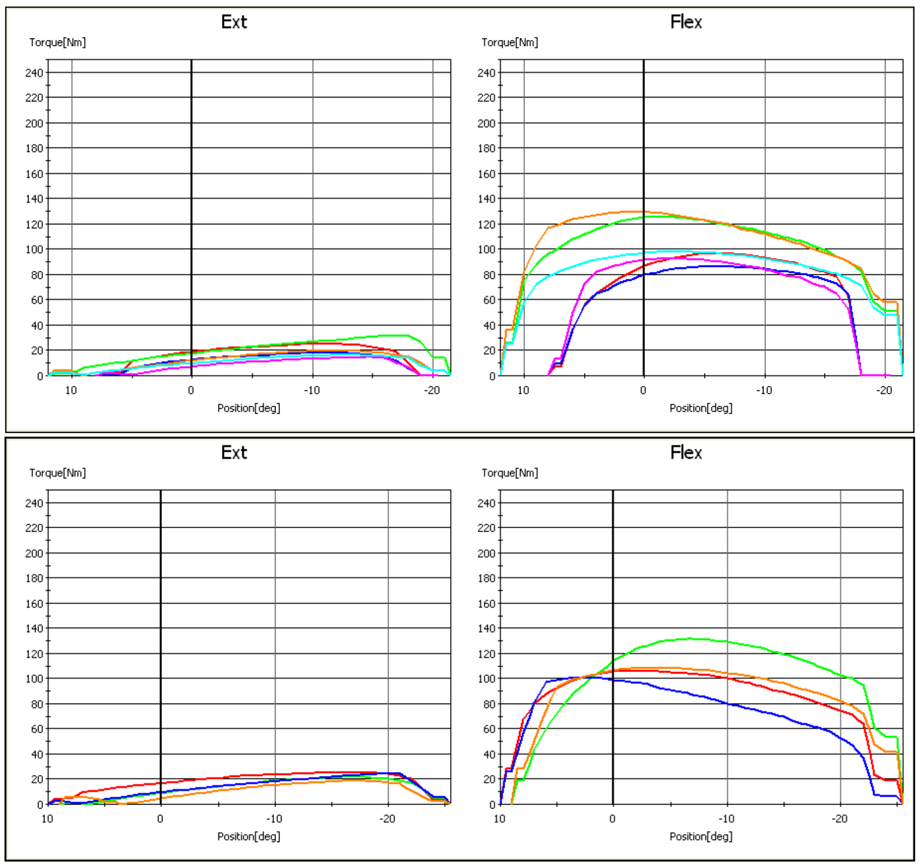
- Muscles always operate in tension, buckling stability is never an issue. Thus, the drives can be built very thin, flexible, lightweight and in any cross section, which allows for optimum space usage. This also helps to minimise system inertia, as masses can be placed where their inertia-related effects are minimal.
- There are very few (if any) cases, in which loads and thus necessary forces for operation of the system are identical in quadrant I & II to the ones needed in quadrant III & IV. This allows, to optimise the drive size and weight for both movement directions separately, thus further reducing overall system inertia.
- Minimal total inertia means, that the power needed to move the system and thus energy consumption is kept to a minimum. A substantial advantage for survival until the arrival of Supermarkets.
- Separate optimisation of the two drive chains, each consisting of muscle and tendons, gives the opportunity, to adapt the overall system in an optimal way to its actual loading conditions.

Muscular "dysbalance" is therefore a basic design feature of the human body and a key point for performance!

The equations, design rules and arguments presented so far lead to the conclusion, that for each joint or arthron there will be a specific optimal asymmetry or "dysbalance". This optimum will be different for different professions and will depend mostly on relative sizes of system inertia related forces (dominant when high movement speeds are involved) and gravity related forces.

Examples:

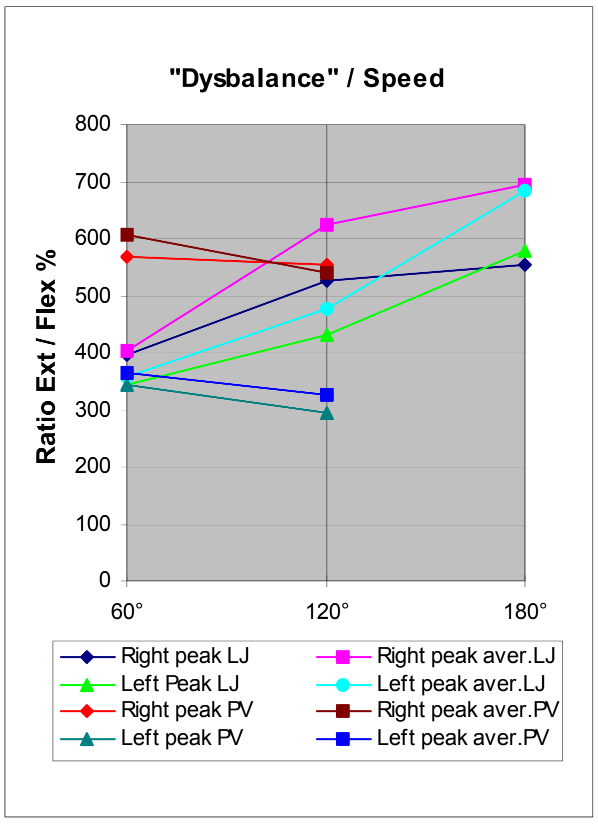
First, some measurements of the left and right ankle joint made with a world class athlete (long jump) and a professional in pole vault are presented. Measurements were made in isokinetic concentric / concentric mode. It has to be considered, that with the small movement angle involved, isokinetic range at 180°/s is close to 0.



For both measurements, the following color-coding is used:

Speed	Right leg	Left leg
60°/s	green	red
120°/s	brown	dark blue
180°/s	magenta	light blue

For interpretation of measurement curves and "Dysbalance" / Speed evaluation it has to be noted, that curves show movement with highest work during half-cycle while "Dysbalance"-evaluation is based on peak torque and average peak torque of several movements. It can be clearly seen, that both athletes have very different, strongly speed-dependent "dysbalances". They also differ substantially from the values found in literature (Berg et. al. 1985, Alexander 1990 and others), which themselves vary from 200% to 400% for the ankle joint.



What is Balance ?

If at all, intra-joint balance can be defined as a **speed dependent,** average peak-torque ratio between agonists and antagonists for an average population. However, depending on profession or training, wide deviations have to be expected from such a **typical value**. This is mainly due to the fact, that nature is a very good engineer and extremely efficient in optimising energy consumption versus performance.

Dysbalance could be defined as a limit, where joint stability or functionality starts to be impaired. It is currently beyond our knowledge, how much scientific work has been done already in this direction.

Balance in real life, Conclusions:

Until here, only **intra-joint balance** has been discussed. In normal life as well as in athletics, there are nearly no movements where joints are just operating in a sequential manner. Sequential has to be understood in that way, that the movement of the first arthron will be finished until the next arthron in the chain starts. When joints move simultaneous, balance gets a new meaning. It now has to be made sure, that not one joint overdrives the other, as otherwise performance will be substantially reduced. For overall performance, **inter-jont balance** and coordination will probably be of even higher importance then **intra-joint balance**.

- Imbalance is an advantage of biological systems, which allows to minimise energy consumption while maximising performance.
- Inter-joint balance is minimum as important as intra-joint balance for overall performance, but we know little about any research work and common knowledge in this direction.
- Imbalance can possibly be defined as limit-values, beyond which joint-stability or functionality starts to be impaired.