On the quasi-static and dynamic stability of the shoulder

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ABSTRACT - In addition to force and moment equilibrium, the stability of this equili-brium is an essential requirement for adequate functioning of the shoulder joint. In this paper the effect of forces (in particular muscle forces and gravity) on the joint stability is assessed. Primarily, this is done using a quasi-static approach, where only the forces and their spring-like behaviour are taken into account, but the possibly dynamic nature of the force build-up after a joint angle deviation is neglected. To obtain clear insight, the very simple configuration of a hinge joint is used for the analysis. Subsequently, the implications of the dynamic nature of the force generation (which most physical forces show to some extent) are discussed.

For the specific geometry of the shoulder muscles, the presence of forces in the muscles as such is shown to have an often destabilizing effect on the joint angle. The intrinsic stiffness of the muscles somewhat compensates for this effect when the muscle is at a relatively short length, but many times not sufficient to give the total muscle activation a stabilizing effect. The muscle stiffness deriving from the reflexive control of the shoulder muscles must be taken into account to explain the full stabilizing effect of co-contraction. From the dynamic analysis it follows that neglecting the dynamic nature of the muscle forces gives an unrealistic view of the possibilities and limitations of the musculoskeletal system performance.

INTRODUCTION

The aim of the present article is to investigate the postural stability of the shoulder joint. For posture maintenance, it is required that the forces and moments acting on the limb are in equilibrium. For joints that can be described as hinges or ball joints, the *force moment* equilibrium is primarily of importance. However, the fact that there is equilibrium does not mean that this equilibrium is stable. In essence, there are two types of equilibrium: *stable* and *unstable.* A stable equilibrium implies that when a transient disturbing force is applied to the system, which afterwards is left to itself, the system will return to its original position. Instability means that the effect of even very small disturbing forces increases in time, and the slightest force on the system is sufficient to make it leave its equilibrium position. Evidently this is in contradiction with the requirements of posture control; hence for posture control there must be (force moment) equilibrium *and* stability.

In this paper, two approaches are used to get more insight into the postural stability of the arm: The quasi-static approach and the dynamic systems approach. In the quasi-static approach, all dynamic properties of the system are neglected; it is assumed that the forces that occur after a perturbation of the equilibrium position occur instantaneously, without any dynamic effect between the angle perturbation and the restoring force. A spring is a good example of such a force (and almost the only one); but in the analysis also other forces can be included, in which case only the quasi-static component is regarded. However, this approach is limited. If a quasi-static analysis indicates that a system is unstable, is also unstable as a dynamic system; but when the quasi-static analysis predicts the system to be stable, there is no guarantee that the corresponding dynamic system is also stable (unless it consists of passive elements only: masses, springs and dampers).

The second approach is a dynamic analysis of the system. In this approach, the dynamic characteristics of all elements in the system are described. With the methods of control theory, the stability of the dynamic model can be investigated, taking into account all dynamic effects between the position perturbation and the reaction of the system on this perturbation. Reflexive forces must be considered as dynamic force. In steady state, their behaviour can be described like that of a spring, but during a transient disturbance, the effects of the sensory time delays and the muscle activation dynamics limits the speed of response of the muscle force. Because of these lags, the magnitude of response of the reflexes may not be too high, otherwise the fierce but delayed response of the muscle force may increase the angular deviations instead of reducing them. The effect of the reflexes, which are an important contributing factor to the joint stability can only be assessed in a dynamic analysis.

Both types of analysis will be performed on a system of highly simplified geometry: a hinge joint. While this may seem an oversimplification, it is in fact very useful for obtaining insight which can hardly be obtained with a more complex model.

QUASI-STATIC STABILITY

The simplest way to analyse the system stability is the quasi-static approach. In this approach, only the quasi-static part of the system is taken into account, i.e. the spring-like characteristics. For physical angular springs, the moment ΔM, that ensues after a deviation of the angle from the equilibrium position, is proportional to the angle deviation $\Delta\phi$, and oppositely directed,

$$\Delta M = -k\ \Delta\phi \qquad (1)$$

with the spring constant k being positive by definition. Because the moment change is oppositely directed to the angle deviation, its effect is to restore the joint angle.

For a general force Fi that has a force moment Mi around the joint, the force moment can be written (in a first-order approximation) as $M = M_{i,o} + dM_i/d\phi\ \Delta\phi$. In this description, the moment has a constant term $M_{i,o}$ and an angle-dependent term $dM_i/d\phi\ d\phi$.When the first-order approximations of the moments of all forces acting on the system are summed together, all the constant terms of the individual moments sum up to zero: there is moment equilibrium! What remains is the sum of the angle-dependent terms. Hence the change of the total joint moment due to a change of joint angle can be expressed as:

$$\Delta M = (\Sigma\ dM_i/d\phi)\ \Delta\phi = dM/d\phi\ \Delta\phi \qquad (2)$$

The sum of the individual derivatives $\Sigma dM/d\phi$ for convenience is called $dM/d\phi$, the change of the total moment around the joint due to an angle change. When this expression is compared to Eq. (1), it is seen that the change of moment with the change of angle is a spring-like effect, with the spring constant of the 'moment spring' caused by the action of all moments on the joint equal to:

$$k = -dM/d\phi \qquad (3)$$

The total $dM/d\phi$ term of all muscles must be negative for the spring constant of these muscles to be positive, i.e. for the spring to act like a physical spring. In other words: the change of the moment must have the opposite direction as the change of the angle, $dM/d\phi < 0$, for the system to be stable in the quasi-static sense. If on the contrary $dM/d\phi$ has a positive value, ΔM and $\Delta\phi$ have the same sign, i.e. the moment change amplifies the effect of the joint angle deviation. This indicates instability of the system.

For the present joint geometry consisting of a hinge joint only, the moment of a force can be written as the product of the moment arm r and the force magnitude F : $M = r\,F$. The moment arm and the force magnitude may both be a function of the joint angle. Hence the derivative $dM/d\phi$ must be determined using the chain rule:

$$dM/d\phi = dr/d\phi\ F + r\ dF/d\phi \qquad (4)$$

Thus, the moment change is seen to exist of two terms. The term $dr/d\phi\ F$ is called the *force contribution to stability,* because it is the *force* magnitude that determines this term, in combination with the musculoskeletal geometry. The term $r\ dF/d\phi$ will be called the stiffness contribution to stability because the stiffness of the muscle (or other actuator) determines the magnitude, combined with the musculoskeletal geometry. For muscles with a purely kinematically determined line of action, e.g. muscles having a straight line of action between origin and insertion, or muscles wrapped over a bony contour, the angular stiffness $dF/d\phi$ can be written as $dF/d\phi = dF/dl\ dl/d\phi = -\ dF/dl\ r = -\ k_{mus}\ r^2$. For these common types of muscles, the term $dM/d\phi$ can be written as:

$$dM/d\phi = dr/d\phi\ F - r^2\ k_{mus} \qquad (5)$$

Hence, it can be seen that the muscle stiffness is stabilizing when the muscle stiffness is positive (then $-\ r^2\ k_{mus}$ is negative, and a negative $dM/d\phi$ indicates stability). Only when the muscle stiffness is negative the stiffness contribution is destabilizing, which may happen when the muscle is longer than its optimal length and there is no (positive) reflex-

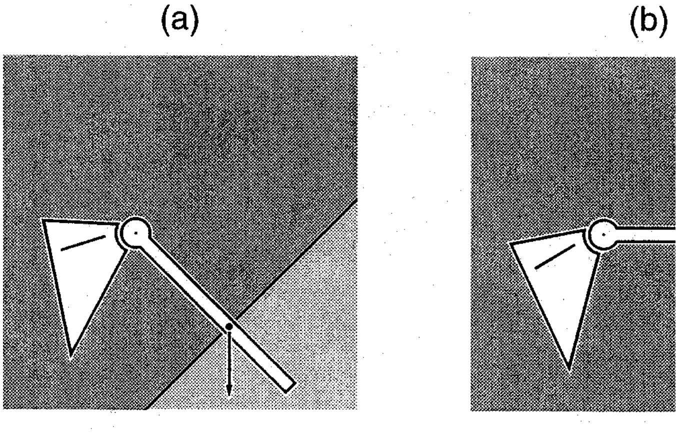

Figure 1-*The contribution of gravity to postural stability, graphically indicated. (a) If the gravity force vector points into the light area (which must be thought fixed to the arm), as it does for the lower elevation angles, its effect is stabilizing. (b) At 90° elevation the effect of gravity on stability is neutral. (c) For higher elevation angles, the gravity force vector points into the dark area, indicating its destabilizing effect.*

ive stiffness to compensate for the negative intrinsic stiffness.

For gravity, the stiffness contribution to stability equals zero, because the gravity force has no stiffness ($dF/d\phi=0$). For forces with a constant moment arm, e.g. wrapped around a spherical bony contour, the force contribution equals zero, because the moment arm is independent of the joint angle ($dr/d\phi=0$).

For specific types of muscles, the effect on stability can be depicted graphically. In Figure 1, this has been done for the effect of gravity on (quasi-static) stability. For elevation angles lower than 90°, gravity has a stabilizing effect; for elevation angles higher than 90°, gravity has a destabilizing effect; at 90°humeral elevation, the effect of gravity on stability is neutral.

For the force contribution of a point-to-point muscle, it can be shown that the force contribution to stability depends exclusively on the location of the origin, relative to the joint centre of rotation and to the insertion point on the arm. Hence it is possible to define areas relative to the arm where the muscle origin must lie to have a stabilizing force contribution. This is shown in Figure 2. From this figure it is seen that the force contribution to stability is almost exclusively destabilizing for the region where the shoulder muscle origins lie. Amongst others, this means that when the muscle force is increased (e.g. by co-contraction), the force contribution to stability gets more destabilizing! It must be kept in mind that the figure is only valid for point-to-point muscles. For muscles with a constant moment arm, like the rotator cuff muscles which wrap around the spherical humeral head, the force contribution to stability is neutral instead of destabilizing, i.e. not disadvantageous.

The muscles also have a stiffness contribution to stability, and the force and stiffness contributions must be added to evaluate the total effect of contraction of the muscle on stability. The primary source of quasi-static stiffness of the muscles is the active force-length relationship. As the length of the muscle changes (quasi-statically), the force at a constant activation of the muscle changes, because the muscle reaches another point of its force-length relationship. If the muscle is shorter than its optimum length, an elongation of the muscle leads to an increased muscle force, i.e. the muscle acts as a normal spring, and has a stabilizing influence as concerns its stiffness contribution. If the muscle is above its optimum length, the force decreases with a lengthening of the muscle, i.e. the muscle has a negative spring constant, and its spring-like effect is destabilizing. The passive force-length relation is not taken into account, as in the mid-range of the working area of the arm this is only a minor source of stiffness compared to the muscles. When the majority of the muscles are on their positive force-length slope, it is possible that the force contribution and the stiffness contribution from the force-length relationship together add up to a stabilizing effect. In Figure 3 this possibility is investigated. From this figure it is seen that when the two effects are combined, and the muscle is on the appropriate part of the force-length relationship, the region where the muscle origins may lie for the muscle to have a stabilizing effect has clearly increased. Yet, a considerable part of the thorax region is still outside this range, meaning that the muscles which originate there still have a destabilizing effect when contracted (except for constant-moment arm muscles like the rotator cuff muscles, for which the figures do not apply; but in co-contraction it is not only these muscles that are involved). Furthermore, not all muscles can be at the same time at the length for which the maximum stiffness is obtained. For these reasons, it is not likely that the quasi-static effect of co-contraction adds much to the stability of the joint. Then where does the known stabilizing effect of co-contraction comes from?

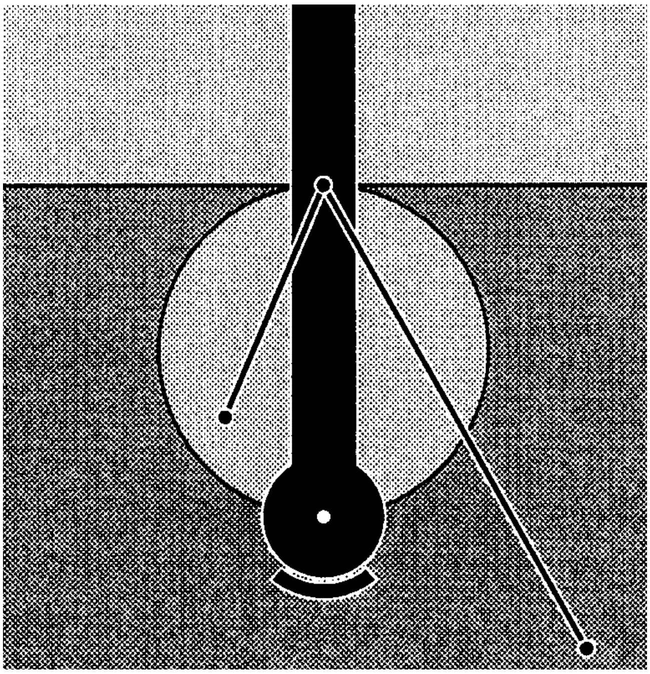

Figure 2-*The force contribution of a point-to-point muscle. If the origin of the muscle lies within the light area (which again must be thought of as fixed to the arm), the force contribution of the muscle is stabilizing. For most shoulder muscles, the origin lies in the dark area, indicating a destabilizing force contribution.*

DYNAMIC STABILITY

In the previous analysis, muscle reflexes were not included. This is because they are essentially dynamic forces. Certainly they have a quasi-static spring-like effect that is an essential element of their behaviour. However, the gain of the feedback loop, i.e. the magnitude of the moment response relative to the angle change, determines their contribution to stability. In the quasi-static approach, there is no upper limit to this gain. However, the reflexive forces occur delayed because of the sensory time delays and the activation dynamics of the muscles, and for this reason their gain cannot be increased too far. In that case, the delayed response does not cause a decrease of the angle deviation to zero, but causes a larger deviation in the other direction, which again leads to a still larger overcompensation: the system is unstable. The phase lag in the response is an essential limitation to the effectiveness of the reflexes. The larger the phase lag, the smaller the admissible feedback gain before instability results.

In Figure 4, a dynamic version of the earlier quasi-static model is represented in the form of a control scheme. In the figure, five feedback paths are shown. Two of these represent the passive visco-elasticity of the arm (stiffness $k\phi$ and viscosity $b\phi$). The other three are the reflexive feedback paths. Here kl and kv represent the length-and-velocity feedback that results from projection of the muscle spindle sensory signals to the motor neurons. The feedback gain of the sensory signal from the Golgi tendon organs is denoted as kf. It is seen that at the summing junction where the feedback paths come together (corresponding to some extent to the motor neuron), the summation signs are the same as those that are found in the mono-synaptic projections from the muscle spindles (excitatory, positive feedback) and from the bi-synaptic connections of the Golgi tendon organs (inhibitory, negative feedback). However, from the control scheme it is seen that each of the three loops has a negative sign within the control loop, as is appropriate for effective feedback control: the force feedback path at the summing junction, the length and velocity feedback path for another reason. The muscle moment equals the muscle force times the moment arm r, but the angle change that results from this moment shortens the muscle:

$\Delta l = - r \Delta\phi$ and $v = - r \phi$.

This causes a negative sign also in the length-and-velocity feedback path.

It was mentioned before that the larger the phase lag in the loop, the smaller the allowable feedback gain. When looking at the three feedback paths of Figure 4, it is seen that from force feedback to length feedback, the dynamics in the loop increase (each time an extra integrator in the loop adding, plus the effect of the time delays). Hence, the inner loops can be controlled more tightly than the outer loops. However, there is also an interaction: as the feedback gain of the force feedback loop is increased, the dynamics of the muscle plus force feedback become faster. For that reason, the velocity feedback loop experiences a smaller lag, and its gain can also be increased, making that loop faster. Finally, the length feedback path experiences a phase lag that is decreased by both the force feed-

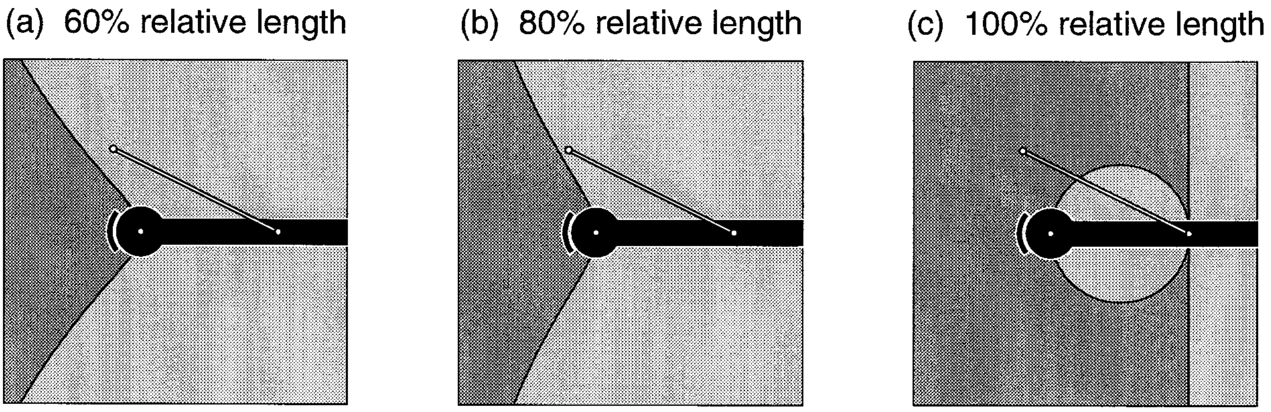

Figure 3 -*The combined effect of the force contribution and the stiffness contribution from the active force-length relationship, for a point-to-point muscle. (a) For muscles at 60% of their optimum length, the area of muscle origins for which the corresponding muscle as a whole has a stabilizing effect is considerably increased, yet it excludes large parts of the thorax. (b) Stability areas for muscles at 80% of their optimum length. (c) For muscles at optimum length, the stability areas are the same as in Figure 2, as the stiffness contribution is zero. For larger lengths the stabilizing areas are even smaller. (not shown)*

back and the velocity feedback, hence the length feedback gain can also be increased, and indeed considerably. It is this length feedback gain that determines the final quasi-static stiffness of the loop. However, it is seen that the other feedback loops, which do not contribute directly to the reflexive stiffness, nonetheless serve to increase the effectiveness of the length feedback loop.

The major part of the effectiveness of co-contraction also derives from such dynamic effects. Co-contraction can be seen as an addition to the passive stiffness $k\phi$ and viscosity $b\phi$ of the system. The stiffness $k\phi$ equals the combined force and stiffness contributions to stability from the quasi-static analysis of the system; it was seen that no large stabilizing effect must be expected from this factor, if any. However, the viscosity $b\phi$ of the system increases also under co-contraction. In the same way as before, it can be seen that this viscosity forms a feedback loop inside the reflexive length feedback path; its presence decreases the phase lags that the reflexive feedback control is limited by. Formulated in a more accurate way, the viscosity from the muscle co-contraction supplies more damping to the system than the reflexive system can obtain itself; and due to that fact the reflexive length feedback gain can be increased. Thus effectively the stiffness of the system has been increased by the co-contraction, but via the mechanism of an increased length feedback gain.

THE DELFT SCHOULDER MODEL UNDER REFLEXIVE CONROL

The final goal of the models described above, which are discussed in much more detail in (Rozendaal, 1997), is to increase the understanding of the real shoulder. However, access to the shoulder for detailed measurement is very difficult. Therefore, the model approach is the next best. For this purpose, the Delft Shoulder Model (Van der Helm, 1991) has been extended with a dynamic model of the muscles and a control model which includes the same feedback loops as are seen in Figure 4. Preliminary simulations with the model show the same characteristics as expected from the simpler quasi-static and dynamic models.

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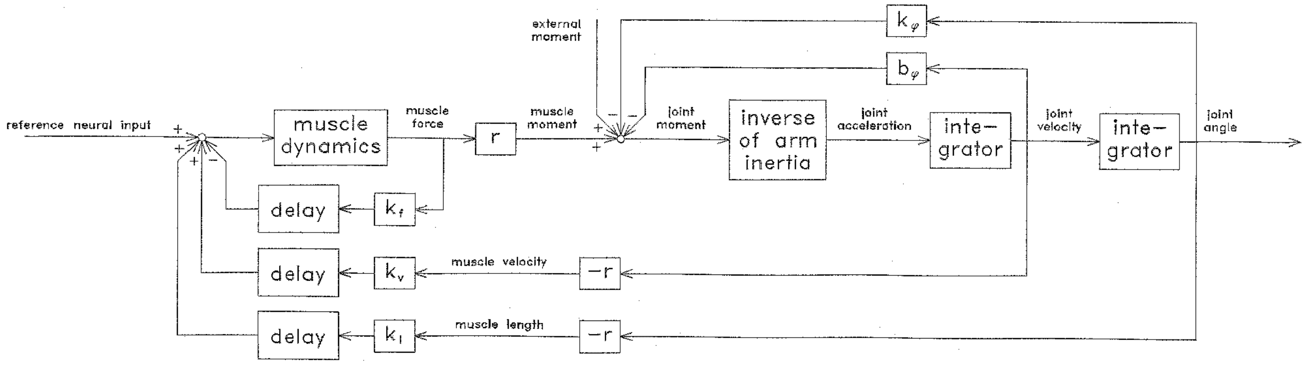

Figure 4-*Control scheme showing the intrinsic (k_ϕ,b_ϕ) and reflexive (k_l,k_v and k_f) feedback paths. Parameters: k_ϕ intrinsic stiffness, b_ϕ intrinsic viscosity, k_l length feedback gain, k_v velocity feedback gain, k_f force feedback gain, r moment arm.*