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Effect of muscle properties on postural stability of simple musculoskeletal system

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During movement and also in situations of keeping a desired posture, many muscles have to produce defined forces. In featuring selfstabilizing properties, the mechanical system may help to simplify the necessary motor control [1]. Due to mechanical feedback of muscle dynamics acting faster than any reflex loop, the actuator itself may contribute to stabilize the musculoskeletal system with respect to perturbations [2].
The purpose was to test the properties of the actuator muscle with respect to stability of posture in a simple musculoskeletal system in a setting of constant activation and to possibly relate stability relevant properties to questions of muscle adaptation.
We chose a simple musculoskeletal system for this analysis. A muscle is connected to a mass via a lever and counteracts the gravitational and inertial force of the mass. This situation may be given in reality in some situations, for example in a waiter holding a tablet, standing on the ball, skiing down a hill etc. The muscle is represented by a contractile component. Elastic muscle properties are neglected. The contractile force equals the product of the activation level, the maximum isometric force, and the normalized values from a parabolic force-length relationship and a Hill-type force-velocity relationship.
Dimensionless formulation reduced the number of system parameters by three since the dimensions of the system parameters can be expressed by the three fundamental quantities length, mass and time. Typical phase portraits of the system were calculated. Fixed points only occurred if the dimensionless force F_{rel} was higher than one, i.e. if the muscle was able to balance the load isometrically at the given level of activation and lever ratio in between muscle lever arm and mass lever arm. A stable fixed point occurred on the ascending limb of the force-length relationship and a non-stable fixed point on the descending limb of the force-length relationship.
We concentrated on the stable fixed point, assuming that the muscle is implemented in a way that stable behaviour of the system is achieved. The stable fixed point of the system was either a stable node or a stable spiral. In the former case the system is critically damped, in the latter exponentially decaying oscillations occur. Which case occurs depends on F_{rel} (at equilibrium corresponding to a value of the force-length relationship f_x of the system: f_x.=1/F_{rel}, Fig. 1A) and the dimensionless parameters *curv* (curvature of the force-velocity relationship) and the maximum system contraction velocity v_{max}^*. Since we did not want the waiter to spill the wine, we defined that critical damping might be of advantage. A functional dependence for the borderline case ‘degenerate node’ in the transition from stable node to stable spiral was derived (Fig. 1A).

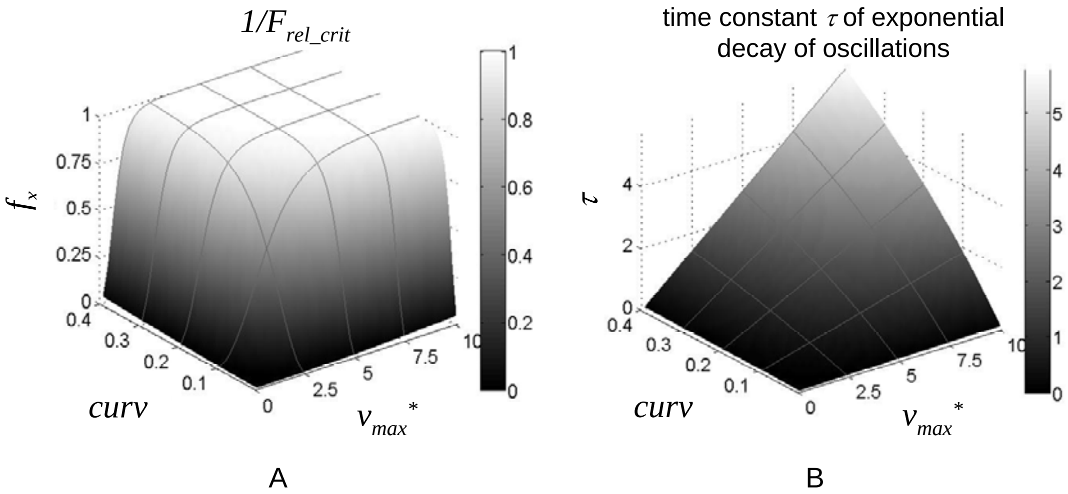

Fig. 1. A) Reciprocal of the dimensionless force F_{rel_crit} for which for rising F_{rel} a transition from critical to undercritical damping occurs. B) Dimensionless time constant τ of exponential decay of oscillations in the state space near the fixed point following a perturbation.

The oscillation frequency increases with increasing F_{rel} due to stiffening of the system. However, the time constant τ, which represents the dimensionless time needed to reduce oscillations following a perturbation near the fixed point by 63 % is independent of F_{rel}. It only depends on the parameters *curv* and v_{max}^* and rises with increasing v_{max}^* and *curv* (Fig. 1B).

The ranges of physiological v_{max}^* and *curv* values of the investigated musculoskeletal system at least partly cover the sensitive ranges seen in Fig. 1A. Low v_{max}^* results in critical damping on the whole ascending limb of the force-length relationship regardless of the *curv* value (Fig. 1A). Increasing muscle lever and fiber length reduce v_{max}^* and support critical damping. The curvature of the force-velocity relationship has strong influence on the occurrence of oscillations in a low range only reached by slow muscle fibers (*curv*<.1, Fig. 1A).

These findings suggest that muscles with low maximum contraction velocity and low *curv* values are appropriate to damp the investigated musculoskeletal system critically in posture related tasks whereas muscles with high maximum contraction velocity and *curv* values are less well suited for this purpose. Indeed, we find muscles with virtually pure slow fiber type acting in similar musculoskeletal systems, e.g. the cat soleus muscle. Also, tests with human subjects indicate critical damping of the lower arm limb. We conclude that stability demands might influence muscle adaptation.

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