

Muscle force–stiffness characteristics influence joint stability: A spine example

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Abstract

Background. The muscle force–stiffness relationship has often been modeled as linear, while in situ muscle research has clearly demonstrated non-linearity. Estimation of rotational joint stability relies on both a muscle's instantaneous pre-perturbation force and stiffness. Under conditions of static equilibrium, a muscle's stiffness will function in a stabilizing manner, while its force can function in either a stabilizing or destabilizing manner depending on the muscle's orientation about the joint.

Methods. A single muscle (rectus abdominis) was modeled and its individual direct stabilizing potential about the L4–L5 spine joint was analyzed. Three force–stiffness relationships were examined: (1) linear; (2) non-linear with moderate stiffness magnitudes; (3) non-linear with higher stiffness magnitudes.

Findings. With a linear force–stiffness relationship, stability increased proportional to muscle force; with a non-linear relationship, stability peaked and subsequently decreased at submaximal muscle forces. When considering the lower, as opposed to the higher non-linear stiffness magnitudes, the stabilizing potential of the muscle peaked at a lower muscle force level and actually became negative (destabilizing) at a critical stiffness magnitude.

Interpretation. It was concluded that a non-linear muscle force–stiffness relationship greatly alters the individual stabilizing potential of the muscle throughout its progression of force development. A muscle's stabilizing contribution may actually peak at and subsequently decrease above a critical submaximal force level. Incorporating this knowledge into stability models may assist in recognizing unstable events that lead to injury at higher levels of muscle activation.

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1. Introduction

Rotational joint stability is primarily dependent on the ability of the surrounding muscles to activate appropriately at any given instant in time. It is a highly dynamic process involving a coordinated interaction between all of the muscles supporting the joint. No single muscle can be defined as most important in provid-

ing stability, since the best stabilizer will migrate among the many muscles contingent on the loading and postural situation (Cholewicki and Van Vliet, 2002; Kavcic and McGill, 2004). Using an analogy of a mast supported by guy wires, the geometry of the guy wires determines the critical load just prior to buckling. In a spine example, the orientation of muscles (guy wires) about the joint has been identified as crucial in determining its stabilizing potential (Potvin and Brown, 2005). These authors were able to mathematically separate a muscle's stabilizing contribution into two components: (1) pre-perturbation tension; (2) pre-perturbation stiffness. In a situation of static equilibrium, a muscle's stiffness will always serve to stabilize a joint; however,

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depending on muscular orientation, its pre-tension may either stabilize or destabilize the joint. For a muscle's pre-tension to be destabilizing, its orientation must be such that upon a small rotational perturbation, the change in its length and moment arm will function to further increase the net moment in the direction of the applied perturbation. In our quest to identify the important variables that determine spine stability, we were motivated to assess the relative effects of estimates of individual muscle force–stiffness relationships. Thus, this short paper was designed to serve as a proof of principle of the potential effect that a non-linear muscle force–stiffness relationship may have on a muscle's contribution to joint stability–spine stability in this example.

The overall stabilizing contribution of a muscle is thus dependent on the magnitude of the relationship between its force and stiffness. This relationship is far from understood, but the prevailing theory is that muscle force and stiffness in the contractile element are produced by the cycling of cross-bridges as the muscle contracts and relaxes (Huxley, 1957). While this relationship is often modeled as linear, various studies examining isometric and isokinetic muscle force and stiffness have demonstrated a non-linear relationship, with the steepness of the stiffness increase degrading with increasing force (Joyce and Rack, 1969; Pousson et al., 1990; Ettema and Huijing, 1994). The majority of this degradation appears to occur at lower force levels. Furthermore, additional passive elastic, tendon, and reflexive stiffness components further add to the non-linearity in the force–stiffness relationship. Hoffer and Andreassen (1981) showed that when accounting for the stiffness added by force recruitment from reflexive pathways, muscle stiffness appears to asymptote at approximately 25% of maximum activation, thus producing a highly non-linear relationship.

In mechanically quantified joint stability research, it has generally been assumed that a muscle's direct contribution to stability increases with force and activation and theoretically peaks at maximum force and effort. This assumption is questioned however, when considering a non-linear force–stiffness relationship, as it becomes possible for a critical point to exist in the muscle force–stiffness spectrum at which the increase in force becomes dominant over the increase in stiffness, thereby potentially decreasing the muscle's contribution to joint stability. The purpose of this paper was to theoretically test this notion, by comparing the joint stabilizing effects of a muscle with a linear force–stiffness relationship to the same muscle after imparting a slight non-linearity into the relationship. It is hypothesized that any non-linearity in the force–stiffness relationship will greatly modify the joint stabilizing effect of individual muscles.

2. Methods

The effect of a single muscle's activation on stability (in this example, the rectus abdominis (RA)) about the lateral bend (LB) axis of the L4–L5 spine joint in upright standing was selected for analysis due to the relatively large destabilizing potential of its pre-tension. Origin and insertion coordinates, with respect to the joint in question, as well as muscle cross-sectional area (CSA) were taken from Cholewicki and McGill (1996) (Table 1 and Fig. 1).

Activation profiles were simulated from 0% to 100% of maximum and subsequent force profiles were calculated from the following equation:

$$F_m = \text{CSA}_m * \delta * \text{ActN} \quad (1)$$

where F_m = muscle force (N); CSA_m = muscle cross-sectional area (m^2); δ = maximum muscle stress (in this study = $350,000 \text{ N/m}^2$) (chosen as a value representative of those reported in the literature (Reid and Costigan, 1987)); ActN = coefficient: activation level non-linearly normalized to maximum (as per Potvin et al., 1996), using a constant (c) of 15 (chosen as a value representative of those found for other muscles (erector spinae, Potvin et al., 1996; biceps brachii, Potvin and Brown, 2004)).

$$\text{ActN} = \frac{100 * e^{(\% \text{activation} * C * 0.001)} - 1}{e^{(-0.1 * C)} - 1} \quad (2)$$

Muscle stiffness was calculated using the following equation from Bergmark (1989):

$$k_m = q \frac{F_m}{L_m} \quad (3)$$

where k_m = muscle stiffness (N/m); q = dimensionless multiplier fitting the relationship between force and stiffness; F_m = muscle force (N); L_m = muscle length (m).

Three stiffness profiles were examined: (i) a linear force–stiffness relationship utilizing a q of 10 (case 1); (ii) a non-linear force–stiffness relationship with q decreasing non-linearly from 10 to 6.4 with force increases at minimum and maximum forces, respectively (case 2); (iii) a non-linear force–stiffness relationship with q decreasing non-linearly from 30 to 19.2 (same degree of non-linearity as case 2) with force increases at minimum and maximum forces, respectively (case 3). These q values were selected to represent a span generally reported in the literature (Crisco and Panjabi, 1991; Cholewicki and McGill, 1995), and to replicate the general form of the non-linear relationship (cases 2 and 3) between muscle force and stiffness seen in the literature (Fig. 2).

The direct muscular contribution to stability was calculated as per Potvin and Brown (2005). Briefly, the potential energy stored in a muscle is a function of both its pre-tension and stiffness

Table 1

Rectus abdominis (RA) origin and insertion coordinates (right side of the body) relative to the L4–L5 joint (x = lateral bend axis; y = axial twist axis; z = flexion–extension axis), cross-sectional area (CSA), and geometric force (F_G) and stiffness (K_G) stabilizing components

	Origin (m)			Insertion (m)			CSA (m ²)	F_G	K_G
	X	Y	Z	X	Y	Z			
RA	.184	.050	.030	.190	.350	.070	.001	-.0584	.0026
L4–L5	.106	.211	.000	–	–	–	–	–	–

F_G and K_G are calculated solely from the geometric components in Eq. 5 ($F_G = \frac{A_z B_z + A_y B_y - r_x^2}{l}$; $K_G = r_x^2$), with force and stiffness set to 1 N and N/m, respectively. L4–L5 joint coordinates are shown as well.

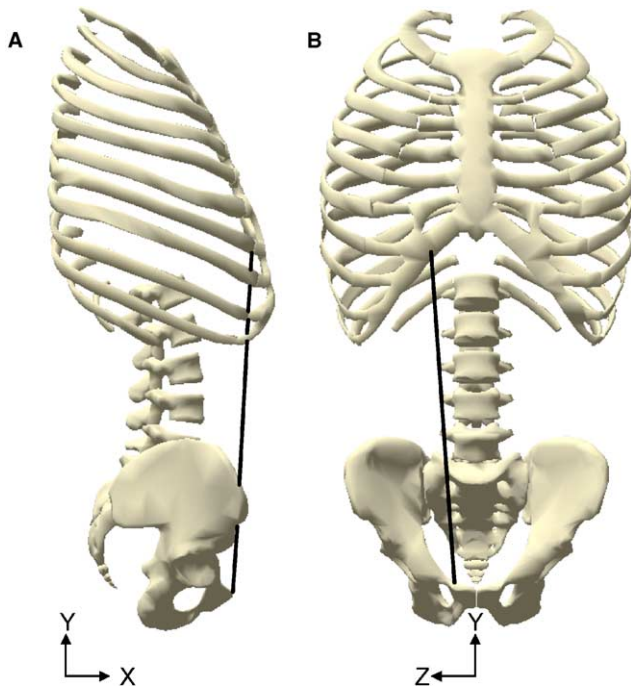


Fig. 1. Approximate model location of the rectus abdominis muscle and L4–L5 spine joint location from (A) right sagittal; and (B) anterior views. (Courtesy Milad Ishac, Department of Kinesiology, University of Waterloo, Canada).

$$V_m = F_m \Delta l_m + \frac{1}{2} k_m \Delta l_m^2 \quad (4)$$

where V_m = the sum of the energy stored and the work done by, or on, the muscle (N m); Δl_m = the change in muscle length for a small rotation (m).

A muscle's contribution to stability was quantified as the second derivative of the muscle's stored elastic potential energy (Crisco and Panjabi, 1992), and thus, after applying appropriate substitutions, yields

$$S_{mx} = F \left(\frac{A_z B_z + A_y B_y - r_x^2}{l} \right) + k r_x^2 \quad (5)$$

where S_{mx} = a muscle's stabilizing contribution about the x -axis (lateral bend axis) of a joint; A_y , A_z = muscle's origin coordinates (in the y and z -axes; axial twist and flexion–extension axes, respectively) with respect to the joint; B_y , B_z = muscle's insertion or nodal coordinates (in the y and z -axes; axial twist and flexion–extension

axes, respectively) with respect to the joint; r_x = muscle's three-dimensional functional moment arm about the x -axis; l = muscle length from its origin to its insertion/nodal point.

3. Results

Both linear and non-linear force–stiffness relationships were simulated for the RA muscle (Fig. 2). The results of the analysis of the muscle's stabilizing contribution to joint stability about the lateral bend axis of the L4–L5 joint demonstrate that with a linear force–stiffness relationship (case 1), stability always continues to increase in its initial direction as force increases (Fig. 3). In other words, if a muscle's initial stabilizing contribution is positive, then it will become more positive in a linear manner as it increases in force. However, for the non-linear force–stiffness relationships simulated here, the muscle's stabilizing contribution peaks at approximately 176 N of force for q 's ranging from 10 to 6.4 (case 2), which corresponds to 50% of maximum force (Fig. 3); and peaks at approximately 325 N of force for q 's ranging from 30 to 19.2 (case 3), which corresponds to 93% of maximum force (Fig. 3). Furthermore, in case 2, the overall effect of the muscle became destabilizing at 92% of maximum force.

4. Discussion

The primary concept demonstrated in this proof of principle study is that a muscle's individual contribution to joint stability may not necessarily peak at its maximum force output. Considering a non-linear relationship between force and stiffness and a muscle whose orientation is such that its pre-tension is destabilizing, there may exist a critical force level at which any additional force increase becomes dominant over the corresponding stiffness increase, thereby reducing the muscle's stabilizing potential. This paper served to theoretically test this principle.

Spine joint buckling has been well understood to occur during “light” loading situations, such as picking up a pencil from the floor or sneezing. This is a result of

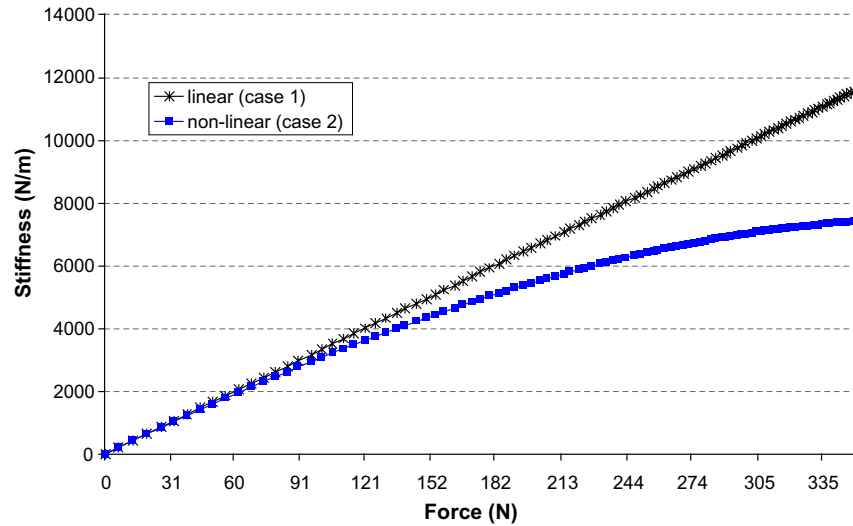


Fig. 2. The linear and non-linear force–stiffness relationships simulated for the RA muscle in cases 1 and 2, respectively.

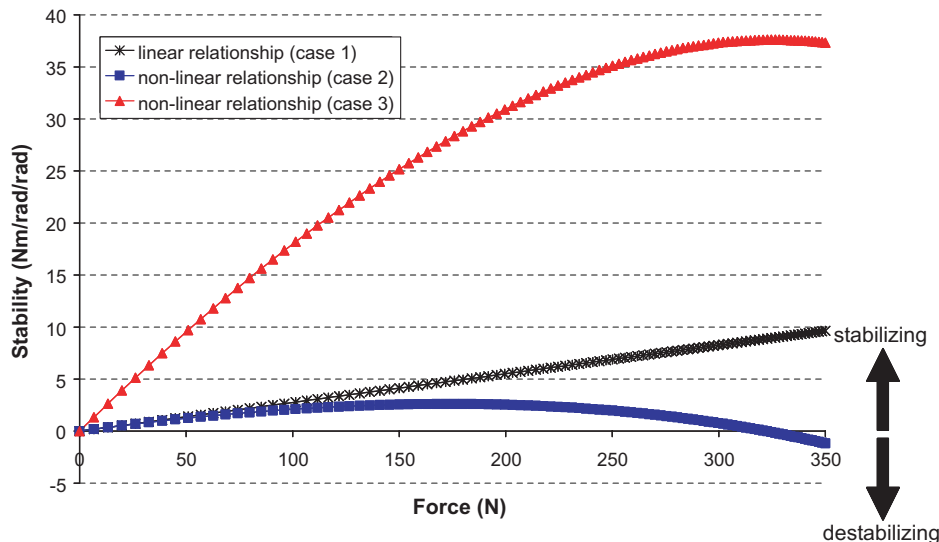


Fig. 3. Stabilizing contribution of the RA muscle about the lateral bend axis of the L4–L5 spine joint in upright standing. The muscle is simulated to have either a linear (case 1) or non-linear (cases 2 and 3) force–stiffness relationship. Cases 2 and 3 have the same degree of non-linearity; case 3 has magnitudes of stiffness three times greater than in case 2. The stabilizing contribution of the muscle is shown over the span of potentially generated isometric forces in the upright standing position. Maximum stabilizing contributions occur at 100%, 50% and 93% of maximum force for cases 1, 2 and 3, respectively.

low levels of activation in the trunk musculature supporting the joints, leading to a relatively low stability margin of safety (defined here as the change in external load which would be required to make the system unstable), which can be surpassed by a sudden increase in applied joint load. However, what has been less well understood are buckling instances that occur under very high loading conditions (i.e. [Cholewicki and McGill, 1992](#)), where the surrounding musculature is highly active, and thus provides a great deal of support to the joint. The apparent dichotomy in the muscle force–stiffness relationship, and its effect on joint stability, may

provide an explanation for this phenomena. As muscles generate force towards maximum, corresponding stiffness increases taper off, thus reducing the stability margin of safety. Based on this, it appears possible that the likelihood of joint buckling is lowest during moderate loading conditions, and becomes higher as loading conditions approach the minimum or maximum of the end loading range.

The equation used here to calculate a muscle's contribution to joint stability ([Potvin and Brown, 2005](#)) is valuable for its ability to separate the geometric contributions of a muscle's pre-tension and stiffness. The

magnitude of these geometric components will depend on the units of measure used in the calculation, and by maintaining the corresponding units for the force and stiffness calculations, one observes that the absolute magnitude in these two measures becomes highly critical in determining the stabilizing potential. For example, if for a given force magnitude the corresponding stiffness is high enough, the critical point where the pre-tension becomes dominant over stiffness will not be reached. Conversely, if the stiffness is decreased relative to the force, it becomes possible that a muscle could actually function in a destabilizing manner about a joint. This has been previously identified by [Shadmehr and Arbib \(1992\)](#), who stated that in order to maintain stability about a single joint system, muscle stiffness must increase at least linearly with force. However, it now must also be noted that the magnitude of the relationship between force and stiffness must be considered in determining whether a muscle functions in a stabilizing or destabilizing manner.

The non-linear force–stiffness relationship simulated in this study was developed in the form of the force–stiffness profile identified for an areflexive (in the absence of reflexive components) muscle complex. [Hoffer and Andreassen \(1981\)](#) and [Sinkjaer et al., 1988](#) both provided evidence for an even greater non-linear relationship when accounting for spinal reflex modulation, with stiffness leveling off between approximately 25% and 50% of maximum activation, and subsequently decreasing at higher activity levels. In this way, the muscle modeled here may be conservative in the effect its force–stiffness relationship would have on joint stability. When considering the entire reflexive muscle complex, peak stability potential may be higher than in the absence of this reflexive component due to a higher peak stiffness. However, the relative amount of degradation in this stabilizing potential would also be greater, as force would continue to increase in the absence of significant stiffness increases above 25% activation. However, one could also argue that reflexive muscular modulation is irrelevant to analyses of mechanical stability, as true mechanical stability is dependent solely on the instantaneous joint stiffness. Regardless, the non-linearity in the force–stiffness relationship simulated in this study is relatively minor, and thus thought to be representative of the data reported for the muscle complex in the absence of reflexes. Therefore the results can be interpreted as, at the very least, a conservative demonstration of the potential effect of this non-linear relationship on joint stability.

The q values reported in the literature range from approximately 0.5 to 50 ([Crisco and Panjabi, 1991](#); [Cholewicki and McGill, 1995](#)), with [Crisco and Panjabi \(1991\)](#) determining an average of 10. The values utilized in the current paper were chosen to represent those values reported in the literature. The q values in cases 2 and

3 had the identical degree of non-linearity with force; however, the values in case 2 were chosen to represent a span most often used in the analysis of muscle/joint stability ([Granata and Orishimo, 2001](#); [Granata and Marras, 2000](#); [Brown and Potvin, 2005](#); [Gardner-Morse et al., 1995](#)), while the q values in case 3 were chosen as a comparison to demonstrate the stabilizing effect of differing q magnitudes. Interestingly, in case 2, the muscle became destabilizing at 92% of maximum force, which corresponded to a q of 6.79. Thus, in this situation, it appears that a q of approximately 6.8 serves as a critical point in the force–stiffness relationship at which this muscle functions in a meta-stable fashion. With higher q , and thus higher stiffness magnitudes, it was observed that the force level at which the stabilizing potential of the muscle peaked shifted closer towards its maximum force. Furthermore, with these higher stiffness magnitudes, the muscle never reached a point in which its destabilizing instantaneous force level became dominant over its stabilizing stiffness level, and thus never functioned in a destabilizing manner about the joint.

The current study examined only the direct stabilizing effect of a single muscle on a single joint, and was not designed as an exhaustive examination of the musculature acting about the lumbar spine. The intent of the paper was to provide evidence that an individual muscle's stabilizing ability may become compromised at high force levels. This potential exists for any muscle whose orientation is such that its instantaneous tension acts in a destabilizing fashion about a joint. Additionally, it should be noted that the nature of the muscle force–stiffness relationship differs depending on how the force is generated. This study simulated only an isometric force–stiffness relationship during which activation was ramped from 0% to 100%. Previous studies have shown a similar magnitude of relationship in isokinetic conditions and in situations in which force was modulated by altering muscle length, with the non-linear relationship being demonstrated for each of these methods of force development ([Ettema and Huijing, 1989, 1994](#)). Therefore, it is felt that the simulation here is sufficient to represent the potential effects of this non-linear relationship on joint stability.

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References

- Bergmark, A., 1989. Stability of the lumbar spine: a study in mechanical engineering. *Acta Orthop. Scand. Suppl.* 60, 3–52.

- Brown, S.H.M., Potvin, J.R., 2005. Constraining spine stability levels in an optimization model leads to the prediction of trunk muscle cocontraction and improved spine compression force estimates. *J. Biomech.* 38, 745–754.
- Cholewicki, J., McGill, S.M., 1992. Lumbar posterior ligament involvement during extremely heavy lifts estimated from fluoroscopic measurements. *J. Biomech.* 25, 17–28.
- Cholewicki, J., McGill, S.M., 1995. Relationship between muscle force and stiffness in the whole mammalian muscle: a simulation study. *J. Biomech. Eng.* 117, 339–342.
- Cholewicki, J., McGill, S.M., 1996. Mechanical stability of the in vivo lumbar spine: implications for injury and chronic low back pain. *Clin. Biomech.* 11, 1–15.
- Cholewicki, J., Van Vliet, J.J., 2002. Relative contribution of trunk muscles to the stability of the lumbar spine during isometric exertions. *Clin. Biomech.* 17, 99–105.
- Crisco, J.J., Panjabi, M.M., 1991. The intersegmental and multisegmental muscles of the Lumbar spine: a biomechanical model comparing lateral stabilizing potential. *Spine* 16, 763–799.
- Crisco, J.J., Panjabi, M.M., 1992. Euler stability of the human ligamentous lumbar spine: part 1 theory. *Clin. Biomech.* 7, 19–26.
- Ettema, G.J.C., Huijting, P.A., 1989. Properties of the tendinous structures and the series elastic component of the EDL muscle-tendon complex of the rat. *J. Biomech.* 22, 1209–1215.
- Ettema, G.J.C., Huijting, P.A., 1994. Skeletal muscle stiffness in static and dynamic contractions. *J. Biomech.* 27, 1361–1368.
- Gardner-Morse, M.G., Stokes, I.A.F., Laible, J.P., 1995. Role of muscles in lumbar spine stability in maximum extension efforts. *J. Orthop. Res.* 13, 802–808.
- Granata, K.P., Marras, W.S., 2000. Cost-benefit of muscle co-contraction in protecting against spinal instability. *Spine* 25, 1398–1404.
- Granata, K.P., Orishimo, K.F., 2001. Response of trunk muscle co-activation to changes in spinal stability. *J. Biomech.* 34, 1117–1123.
- Hoffer, J.A., Andreassen, S., 1981. Regulation of soleus muscle stiffness in pre-mammillary cats: intrinsic and reflex components. *J. Neurophysiol.* 45, 267–285.
- Huxley, A.F., 1957. Muscle structure and theories of contraction. *Prog. Biophys. Biophys. Chem.* 7, 255–318.
- Joyce, G.C., Rack, P.M.H., 1969. Isotonic lengthening and shortening movements of cat soleus muscle. *J. Physiol.* 204, 475–491.
- Kavicic, N., McGill, S.M., 2004. Determining the stabilizing role of individual torso muscles during rehabilitation exercises. *Spine* 29, 1254–1265.
- Potvin, J.R., Brown, S.H.M., 2004. Less is more: high pass filtering, to remove up to 99% of the surface EMG signal power improves EMG-based biceps brachii muscle force estimates. *J. Electromyogr. Kinesiol.* 14, 389–399.
- Potvin, J.R., Brown, S.H.M., 2005. An equation to calculate individual muscle contributions to joint stability. *J. Biomech.* 38, 973–980.
- Potvin, J.R., Norman, R.W., McGill, S.M., 1996. Mechanically corrected EMG for the continuous estimation of erector spinae muscle loading during repetitive lifting. *Eur. J. Appl. Physiol.* 74, 119–132.
- Pousson, M., Van Hoecke, J., Goubel, F., 1990. Changes in elastic characteristics of human muscle induced by eccentric exercise. *J. Biomech.* 23, 343–348.
- Reid, J.G., Costigan, P.A., 1987. Trunk muscle balance and muscular force. *Spine* 12, 783–786.
- Shadmehr, R., Arbib, M.A., 1992. A mathematical analysis of the force-stiffness characteristics of muscles in control of a single joint system. *Biol. Cybern.* 66, 463–477.
- Sinkjaer, T., Toft, E., Andreassen, S., Hornemann, B.C., 1988. Muscle stiffness in human ankle dorsiflexors: intrinsic and reflex components. *J. Neurophysiol.* 60, 1110–1121.