MUSCLE FORCE-STIFFNESS CHARACTERISTICS INFLUENCE JOINT STABILITY: A SPINE EXAMPLE

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INTRODUCTION

The muscle force-stiffness relationship has often been modeled as linear, while in-situ muscle research has clearly demonstrated a non-linearity [1,2]. Estimation of rotational joint stability relies on both a muscle's instantaneous pre-perturbation force and stiffness [3]. 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.

In 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. The purpose of this study 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.

METHODS

A single muscle (rectus abdominis) was modeled and its individual direct stabilizing potential about lateral bend axis of the L4-L5 spine joint was analyzed. Muscle force profiles were simulated from 0 to 100 percent of maximum Muscle stiffness was calculated using the following equation from Bergmark (1989): $k_m = q\frac{F_m}{L_m}$

where: k_m = muscle stiffness ($\frac{N}{m}$)

q = dimensionless multiplier
F_m = muscle force (N)
L_m = muscle length (m)

Force-stiffness relationships were developed by adjusting q through a range of values generally reported in the literature, and to replicate the general form of the non-linear relationship (Profiles 2 and 3) between muscle force and stiffness seen in the literature. Three profiles were examined: 1) linear; 2) non-linear with moderate stiffness magnitudes; 3) non-linear with higher stiffness magnitudes.

RESULTS AND DISCUSSION

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 (Figure 1).

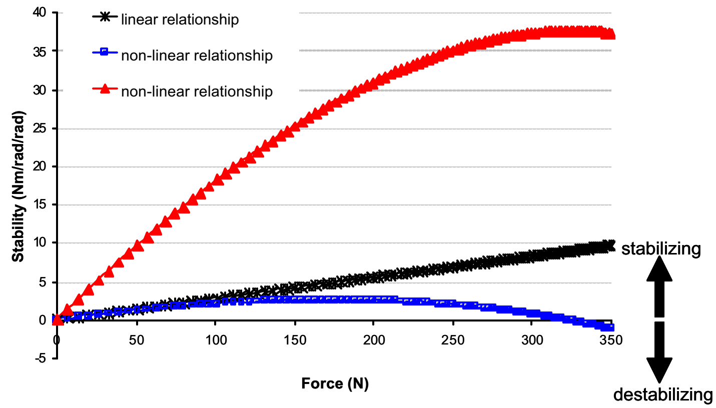

Figure 1: Stabilizing contribution of the RA muscle about the lateral bend axis of the L4L5 spine joint in upright standing. The muscle is simulated to have either a linear or non-linear force-stiffness relationship.

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 it's 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 apparent dichotomy in the muscle force-stiffness relationship, and its effect on joint stability, may provide an explanation for the phenomena of joint buckling under high loading situations. 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 may be lowest during moderate loading conditions, and become higher as loading conditions approach the minimum or maximum of the end loading range.

CONCLUSIONS

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.

REFERENCES

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