# Ankle Muscle Stiffness in the Control of Balance During Quiet Standing

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**Winter, David A., Aftab E. Patla, Shirley Rietdyk, and Milad G. Ishac.** Ankle muscle stiffness in the control of balance during quiet standing. *J Neurophysiol* 85: 2630–2633, 2001. This research presents new data and reanalyzed information to refute the criticisms of our model of stiffness control during quiet standing. A re-review of their references to biomechanical research on muscle ankle stiffness confirmed muscle stiffness estimates of the ankle series elastic elements that agreed closely with our estimates. A new technique is presented that directly estimates the muscle stiffness from the ankle moment (N · m) and sway angle (deg). The linear regression of 10 subjects standing quietly for 10 s estimated the stiffness (N · m/deg) to be safely above the gravitational spring. The $R^2$ scores for this linear regression averaged 0.92, confirming how closely the model approached a perfect spring that would have an $R^2 = 1$. These results confirm our model of a simple muscle stiffness control and refutes the criticisms.

## INTRODUCTION

The concept of a simple muscle stiffness control of balance during quiet standing was introduced by Winter et al. (1998). The crux of their arguments and experimental evidence was that the controlled variable, center of mass (COM), was virtually in phase with the controlling motor variable, center of pressure (COP). The spring stiffness was estimated indirectly from the tuned frequency of the mass, spring, damper mechanical system. If a normal reactive control were present, the efferent and afferent latencies (Horak and Nashner 1986) combined with the biomechanical delays of recruitment of muscle twitches would result in a COP delay of over 100 ms after the COM (Rietdyk et al. 1999). Morasso and Schieppati (1999) have argued that a simple spring stiffness control does exist but that "there must be something in the control circuitry that compensates for the original delays" and that "the phase-lock between COP and COM is a necessary consequence of physical laws." In the presence of such criticism the purpose of this paper is to provide further experimental evidence of a simple spring control at the ankles using direct measures of ankle moments and sway angles. Also, evidence is presented from the stiffness characteristics of the ankle plantarflexors whose nonlinearities provide a simple and stable operating point for control of upright posture.

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## METHODS

Direct measures of stiffness control in quiet standing can be done in two separate ways. The first way requires a full three-dimensional (3D) kinematic and kinetic analysis using two forceplatforms (cf. Rietdyk et al. 1999). Such a technique in the sagittal plane yields the ankle moments and angles for both limbs. A regression of these two variables yields a plot of ankle moment versus ankle angle and the slope of the curve yields the ankle stiffness (N · m/rad) for each ankle. A sum of the left and right ankle stiffness is a direct measure of the anterior/posterior (A/P) stiffness constant that was previously estimated indirectly (Winter et al. 1998).

An alternate and less cumbersome direct estimate of either the A/P and medial/lateral (M/L) stiffness can be made from the readily measured time records of COP and COM (cf. Winter et al. 1998). Figure 1 presents the common inverted pendulum model in the sagittal plane. Here the COM and COP are measured relative to the ankle joint, and the COM is located at a distance $h$ above the ankle joint. The sway is measured by the angle of the line joining the ankle to the center of mass. Body weight (mg) is the weight of the body above the ankle joint, and the vertical reaction force $R$ does not include the reaction force of the feet that are essentially stable in quiet standing, and is equal to body weight. The sum of the left and right ankle moments, $M_a$, is

$$M_a = R \cdot \mathrm{COP} = \mathrm{mg} \cdot \mathrm{COP} \tag{1}$$

$$\theta_{sw} = \mathrm{COM}/h \tag{2}$$

$$\text{Stiffness} \quad K_a = \frac{dM_a}{d\theta_{sw}}$$

Or, if we plot a regression of $M_a$ versus $\theta_{sw}$, the slope of that linear regression is $K_a$, and the closeness of that regression to a straight line (its $R^2$ score) will be a measure of how closely our estimate of $K_a$ resembles a pure spring. For a pure spring the $R^2$ would be 1 reflecting a perfectly straight line.

In balance control studies the latter technique is less complex because it requires only one force platform and has less kinematic markers than a full 3D inverse dynamic biomechanical analysis (a minimum of 3 non-colinear markers are required to define each segment of the body). Thus the direct stiffness estimates reported here will be confined to this latter technique that requires precise and accurate measures of COM. Contrary to the claims of Morasso et al. (1999), the direct estimate from our 14 segment COM model is not "cumbersome" and does not "require a very critical calibration." The 23-marker system in our 14-segment model takes less time to prepare subjects and patients than is needed for 3D clinical gait analysis that

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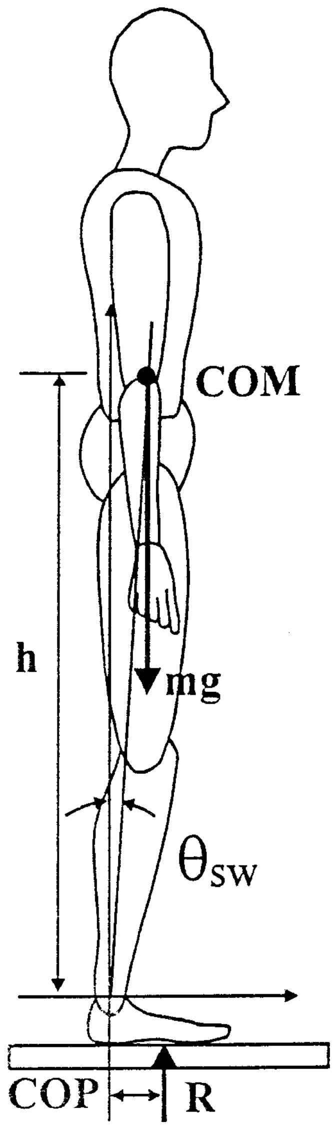


FIG. 1. Inverted pendulum model showing the variables center of mass (COM), center of pressure (COP), body weight (mg), and height, $h$ of COM, from which direct measure of muscle stiffness can be estimated.

have been routinely done for the past decade (cf. Ounpuu et al. 1991). This direct measure of COM is also applicable to clinical studies of balance that routinely require analysis of responses to external perturbations (cf. Horak et al. 1992).

## RESULTS

In a separate set of analyses on 10 adult subjects standing quietly, a full 3D COM and COP biomechanical analysis was conducted. Using *Eqs. 1* and *2*, $M_a(t)$ and $\theta_{sw}(t)$ over the 10 s were analyzed. A sample regression of $M_a$ versus $\theta_{sw}$ for one subject is presented in Fig. 2. The slope of this line is 13.04 N · m/deg or 747.0 N · m/rad. The $R^2$ for this 10-s trial was 0.954. For all 10 subjects the A/P stiffness estimates are reported with their mgh (gravitational spring) in Table 1.

Across all the 10 subjects, the ankle stiffness during quiet standing averaged 858.9 N · m/rad, which was 8.8% higher than the gravitational spring stiffness (mgh), which averaged 789.4 N · m/rad. To achieve this stiffness these subjects had to

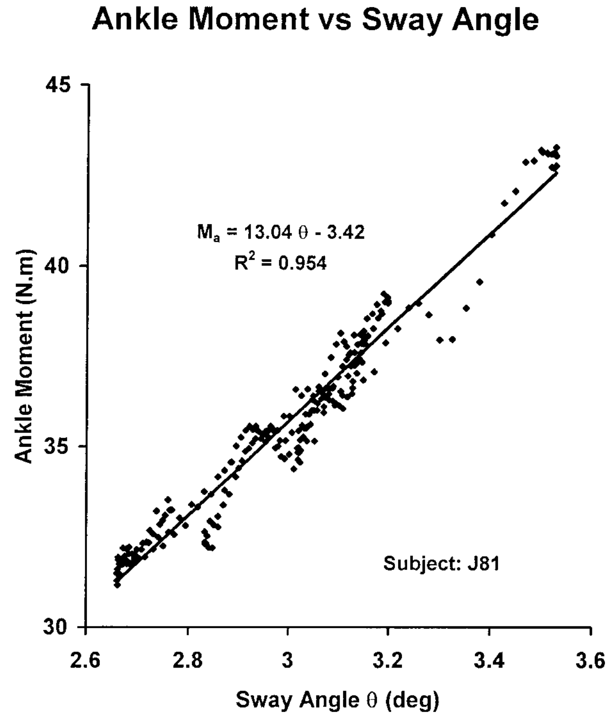


FIG. 2. Regression of net ankle moment $M_a$ vs. sway angle $\theta_{sw}$. Slope of this regression (N · m/deg) is the net ankle stiffness $K_a$. A perfect spring would yield a perfectly straight line regression with an $R^2 = 1$. Thus the $R^2$ score here (0.954) is a measure of how close the ankle spring is to a perfect spring.

sway forward an average of 3.67 ± 0.28°. The $R^2$ score averaged 0.918, which is a measure of how close the ankle stiffness approached that of an ideal spring. Because the subjects in this study were assessed for only 10 s, the magnitude of their changes in sway and ankle moments were somewhat less that if they were assessed over longer periods (Winter et al. 1998).

## DISCUSSION

None of the studies of ankle stiffness reported in the literature replicated the quiet standing conditions in our study. Hof (1998) had his subjects standing with the ankle in a special measuring device, but the subjects balanced themselves with their hands on a rod; he reported muscle stiffnesses of 250–400 N · m/rad. When we consider what the mgh threshold

TABLE 1. *Quiet standing A/P ankle stiffness estimates and sway angle*

| Subject | mgh, N · m/rad | $K_a$, N · m/rad | $R^2$ | Mean $\theta_{sw}$, deg | RMS $\theta_{sw}$, deg |
|---|---|---|---|---|---|
| J73 | 796.5 | 842.7 | 0.964 | 2.29 | 0.28 |
| J74 | 838.2 | 881.3 | 0.882 | 3.42 | 0.18 |
| J75 | 711.2 | 757.8 | 0.843 | 5.04 | 0.33 |
| J76 | 935.7 | 943.6 | 0.918 | 3.61 | 0.28 |
| J77 | 898.7 | 1041.2 | 0.941 | 3.12 | 0.16 |
| J78 | 639.2 | 754.7 | 0.883 | 3.83 | 0.25 |
| J79 | 782.4 | 784.8 | 0.989 | 5.58 | 0.80 |
| J80 | 831.6 | 899.1 | 0.948 | 5.54 | 0.18 |
| J81 | 672.1 | 747.0 | 0.954 | 3.04 | 0.22 |
| J82 | 788.6 | 937.1 | 0.858 | 3.23 | 0.08 |
| Average | 789.4 | 858.9 | 0.918 | 3.67 | 0.28 |

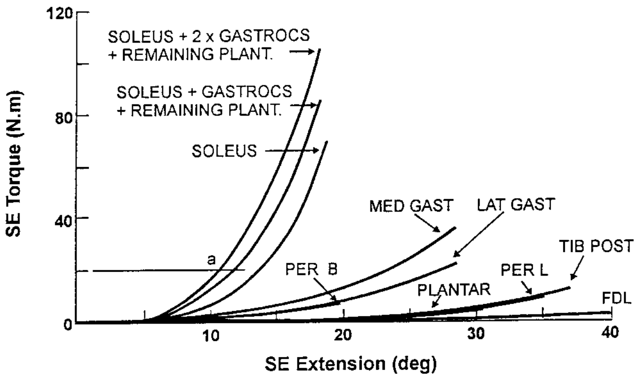


FIG. 3. Series elastic curves for the plantarflexor muscles replicated from Fig. 5 in Winters and Stark (1988). Two new summation curves are plotted: *1*) sum of soleus and gastrocnemii and remaining plantarflexors and *2*) a 2nd summation to account for the fact that the subject was lying prone with knee flexed, here the gastrocnemii contributed proportionally to their physiological cross-section area. For this subject with a muscle tone of 20 N · m, the operating point "a" is predicted.

value was for both limbs, his study would predict 500–800 N · m/rad, which is close to the threshold of mgh = 674 N · m/rad that we predicted for a 68-kg subject. All the other studies had their subjects lying prone with varying degrees of knee flexion. An examination of the series elastic characteristics of the plantar-flexor muscles yields an estimate of the muscle stiffness. A replication from such a study by Winters and Stark (1988), including the summation of all series elastic components of muscles involved, is presented in Fig. 3. For an 80-kg adult standing with his COP 5 cm anterior to the ankle joint, the total ankle moment would be about 40 N · m. Thus with a muscle tone of 20 N · m per ankle, the ankle stiffness can be estimated from the slope of this nonlinear summation curve at the operating "a" point in Fig. 3. Two summation curves are plotted: *1*) sum of soleus and gastrocnemii and remaining plantarflexors and *2*) sum of soleus and two times gastrocnemius and remaining plantarflexors. This second summation is based on the assumption that the gastrocnemii (which were shortened in this experiment because the subject was lying prone with knee flexed) to contribute proportionally to their physiological cross-section area, which is just over half of that of the soleus. The slope of this final summation curve is 6.05 N · m/deg. Thus for two ankles the combined stiffness would be predicted to be ~700 N · m/rad. This again is just below the values we estimated for subjects who were standing with their ankles slightly dorsiflexed and supporting themselves entirely by their plantarflexors. The functional importance of the nonlinear characteristics of these postural muscles must be emphasized. A stable operating point results from this nonlinearity. If the subject were to sway forward, the slope increases, and if he were to sway backward, the slope decreases. Thus the stable operating point is when the subject sways sufficiently to an operating point where the slope safely exceeds the mgh gravitational threshold.

Morasso and Schieppati (1999) developed an inverted pendulum model that incorporated a spring control that was similar to the model developed by Winter et al. (1998). Morasso and Schieppati in their model claim that the in-phase relationship between COP and COM that we found was not a function of a simple spring control. In the direct method reported here, the in-phase relationship is evident between $M_a$ and $\theta_{sw}$, which, from *Eqs. 1* and *2,* reinforces the in-phase relationship between COP and COM. Morasso and Schieppati presented a theoretical reactive control model that also result in COP and COM to be in phase, but their reactive feedback model erroneously contained no afferent or efferent transmission delays.

Both reports showed that the borderline stiffness required to overcome gravity was mgh, where *h* is the height of the COM above the ankle joints. Thus a spring of stiffness mgh N · m/rad was the minimum required at the ankle joints to overcome the unbalancing gravitational forces. However, Morasso and Schieppati (1999) assumed the presence of noise (white noise plus quasi-periodic spike noise) but gave no reference as to where this noise is assumed to be located. However, if we assume that they are referring to the neural spike train of action potentials seen at the motor endpoint, we can agree that these impulses will result in some noise due to the resultant train of twitches seen at the muscle tendon. The noise in the muscle stiffness controller is very low frequency and low in amplitude. Muscle stiffness is controlled by muscle tone, which is a summation of recruited muscle twitches in the balance control muscles. Milner-Brown et al. (1973) showed that the twitches were a critically damped impulse response. The soleus, for example, with twitch times, *T,* can be represented by a low-pass mechanical filter. For a critically damped second-order system, the cutoff frequency of the filter is related to the time-to-peak of the impulse response, *T,* by

$$f_c = \frac{1}{2\pi T} \qquad (3)$$

For the soleus, with a twitch time over 100 ms, $f_c$ = 1.5 Hz. Thus the COP frequency response would be predicted to have negligible power above 5 Hz, and this has been reported in the literature (Powell and Dzendolet 1984; Soames and Atha 1982; Tokumasu et al. 1983). An estimate of this ripple can be made from the COP-COM signal from Winter et al. (1998), and this was <0.1 cm on 40 trials for 10 subjects. The amplitude of COP in quiet standing is about 5 cm, thus the noise in the stiffness controller is not only low frequency but is also <2%. Therefore the safe value of the stiffness does not have to exceed the gravitational spring (mgh) by a large amount. Thus the predicted safe stiffness to be 1,050 N · m/rad in excess of mgh proposed by Morasso and Schieppati (1999) is not justified, and our direct estimate of ankle stiffness is sufficient to control posture during quiet standing.

Estimates of static ankle muscle stiffness in the literature (Hof 1998; Winters and Stark 1988) reinforce the results of our indirect method (Winter et al. 1998) and our direct method reported here. The in-phase relationship between COP and COM that would occur in a simple spring control cannot be explained by the Morasso and Schieppati model because their reactive model failed to include afferent and efferent delays. The excess by which Morasso and Schieppati claim stiffness would have to exceed the gravitational load is not justified by their erroneous assumption of spike noise in the motor system. Rather, the noise in the ankle spring is minimal as predicted by the ripple due to summation of twitches in the ankle plantarflexors.

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