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Unified Theory Regarding A/P and M/L Balance in Quiet Stance

DAVID A. WINTER, FRANÇOIS PRINCE, JIM S. FRANK, CORRIE POWELL, AND KARL F. ZABJEK
Department of Kinesiology, University of Waterloo, Waterloo, Ontario N2L 3G1; and Centre de Recherche en G erontologie et G eriatric, H opital Youville, Sherbrooke, Quebec J1H 4C4, Canada

SUMMARY AND CONCLUSIONS

1. Control of posture in quiet stance has been quantified by center of pressure (COP) changes in the anterior-posterior (A/P) and medial-lateral (M/L) directions from a single force platform. Recording from a single force platform, researchers are unable to recognize two separate mechanisms that become evident when two force platforms are used. Depending on the stance position taken, many combinations of an ankle mechanism and a hip (load/unload) mechanism are evident. In side-by-side stance, A/P balance is totally under ankle (plantar/dorsiflexor) control, whereas M/L balance is under hip (abductor/adductor) control. In tandem stance, the A/P balance is dominated by the hip mechanism, with mixed and small or sometimes negligible contributions by the ankle plantar/dorsiflexors: for M/L balance, the reverse is evident; ankle invertors/evertors dominate, with mixed and small contribution from the hip load/unload mechanism. In an intermediate 45° stance position, both ankle and hip mechanisms contribute to the net balance control in totally different ways. In the M/L direction the two strategies reinforce, whereas in the A/P direction the ankle mechanism must overcome and cancel most of the inappropriate contribution by the hip load/unload mechanism. A spatial plot of the separate mechanisms reveals the fact that the random-looking COP scatter plot is nothing more than a spatial and temporal summation of two separate spatial plots. A straight line joining the individual COPs under each foot is the load/unload line controlled by the hip mechanism. At right angles to this load/unload line in the side-by-side and tandem positions is the independent control line by the ankle muscles. In an intermediate standing position, the separate control lines exist, but now the ankle control is not orthogonal to the load/unload line; rather, it acts at an angle of ~60°. The direction of these ankle control and load/unload lines also allows us to pinpoint the muscle groups responsible at the ankle and hip in any of the stance positions.

INTRODUCTION

The vast majority of the investigations of quiet stance regarding into the neuromuscular responses and strategies have been confined to the sagittal plane (cf. Dietz and Berger 1982; Nashner and McCollum 1985). Medial-lateral (M/L) measures of center of pressure (COP) are frequently recorded (cf. Geurts et al. 1993), but the underlying motor mechanisms have not been addressed except by Day et al. (1993), who suggested that lateral movement could be controlled by the hip abductors/adductors in addition to the ankle invertors/evertors. Responses to lateral perturbations have generally been limited to the electromyographic responses of the ankle muscles (Brunt et al. 1992). In the control of quadrupedal stance, Macpherson (1988) has documented a simplified strategy, mainly by the muscles of the cat's hindlimb, to control balance against horizontal support perturbations over a 360° arc. M/L perturbations were con-

trolled by the hip muscles, whereas anterior-posterior (A/P) perturbations were controlled by the ankle and hip muscles. Some researchers (McCollum and Leen 1989) reported ankle responses in the A/P direction but in their theory inferred an ankle response in both directions and have described the boundary as being a 360° "stability cone" with origin at the ankle. Similarly, Collins and DeLuca (1993) have also inferred the same control mechanism in both M/L and A/P directions in their "random-walk" analysis of COP changes. Others have calculated the radius of the M/L and A/P displacements of the COP plots in normal subjects, thereby inferring that M/L and A/P controls are the same (Black et al. 1982). Recently, Winter et al. (1993) reported that in quiet stance with feet side by side on two force platforms the motor responses in the M/L direction were totally dominated by a hip load/unload strategy. Because this hip strategy was orthogonal to the A/P control, it is seen to be completely independent of the ankle strategy.

The primary variable that has been recorded to quantify the time course of postural balance during quiet and perturbed standing has been the net body COP (COP_{net}) from single force platforms. However, the recent partitioning of an independent ankle and hip mechanism in the A/P and M/L directions in side-by-side stance (Winter et al. 1993) is motivation to examine these mechanisms in other postural positions to see whether there is a unifying theory that applies. The purpose of this study is to determine the relative role of each of these motor control strategies when subjects adopt different foot positions: side-by-side stance, tandem stance, and an intermediate position halfway between the two (called 45° position). This intermediate position is not too different from the position adopted by gait-impaired patients during the double support phase of walking; it is a critical rebalancing phase during the gait cycle. On the basis of the findings of Winter et al. (1993), the following motor responses are hypothesized. Because the invertor/evertor ankle joint axes are lined up in tandem stance, the M/L control will be dominated by an ankle strategy (invertor/evertors) whereas the A/P balance could be a combination of ankle control and hip load/unload mechanism. In the intermediate 45° position, neither of the ankle joints are in line; thus the control is predicted to be exerted by both the ankle and the hip load/unload mechanisms.

Background—relationship between center of gravity and COP

Before presenting the theory and methodology, we present this background to clarify the relationship between the center of gravity (COG) and COP. An understanding of the simul-

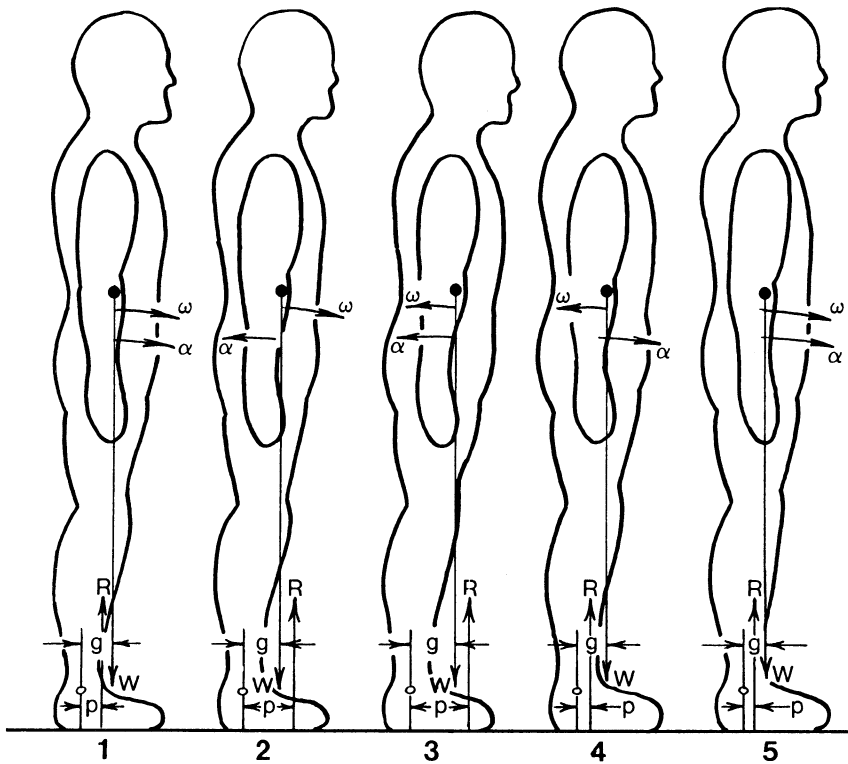


FIG. 1. Subject in quiet stance at 5 different times during the balance of the total body center of gravity (COG) under the control of the net center of pressure (COP_{net}). See text for definition of terms and sequence of events in the balance control of this inverted pendulum.

taneous movement of the COG and COP is necessary to understand how the human body, as an inverted pendulum, is controlled.

The COG of the body is the location of the vertical vector from the center of mass as it intersects the horizontal plane. It is the weighted average of the COG of each body segment. Thus to get the COG we must have the horizontal coordinates of each segment as the body sways, and these estimates are only possible with motion imaging systems. The COP measure is quite independent of the COG. It is also a displacement measure and is the location of the vertical ground reaction vector from a force platform. It is equal and opposite to a weighted average of all downward (action) forces acting between the feet and the force plate. The magnitude and location of these forces are under the control of all the muscles associated with posture and balance. Thus the COP is the net neuromuscular response to control of the passive COG.

The difference between COG and COP is presented in Fig. 1. Here we see a subject swaying back and forth in the sagittal plane while standing erect with feet side by side on a force plate. Each drawing shows the changing situation at five different points over time. Time 1 has the body's COG ahead of the COP, with an angular velocity ω that is assumed to be clockwise at that time. Body weight W is equal and opposite to the vertical reaction force R , and these parallel forces act at distances g and p , respectively, from the ankle joint. Assuming the body to be an inverted pendulum, pivoting about the ankle, a counterclockwise moment equal to Rp and a clockwise moment equal to Wg will be acting. Because $g > p$, then $Wg > Rp$, the body will experience a clockwise angular acceleration α . To correct the forward angular velocity the subject will increase COP (by increasing

plantarflexion activation) such that at time 2 the COP will move anterior to the COG. Now $Rp > Wg$. Thus α will reverse and will start to decrease the angular velocity ω until, at time 3, the time integral of α will result in a reversal of ω . Now both ω and α are counterclockwise and the body is experiencing a backward sway. When the CNS senses that this posterior shift of the COG needs to be corrected, the output of the motor control system decreases plantarflexor activation, thus reducing the COP until it moves posterior to the COG. Thus α will reverse to become clockwise again at time 4, and after a period of time ω will again decrease and reverse and the body will return to the original conditions, as can be seen for time 5. From this sequence of COG and COP conditions it can be seen that the plantarflexors/dorsiflexors in controlling the net ankle moment cause COP to move backward and forward so as to regulate the body's COG. However, it is apparent that the dynamic range of the COP must always be somewhat greater than that of the COG: the COP must be continuously moving anteriorly and posteriorly with respect to the COG. Thus, for example, if the COG were allowed to move within a few centimeters of the toes, it is possible that a corrective movement of the COP to the extremes of the toes would not be adequate to reverse ω . Here the subject would have to move a limb forward to arrest the forward fall.

Figure 2 shows a 7-s record of COP versus COG as a subject stood quietly on a force platform with instructions to stand as still as possible. It is evident that the excursions of the COP are somewhat in excess of the COG. The COP is the neural control variable, whereas the COG is the controlled variable. Thus, for purposes of this paper, when we calculate and interpret the COP waveform we do so in the context of what muscle groups are causing the COP to

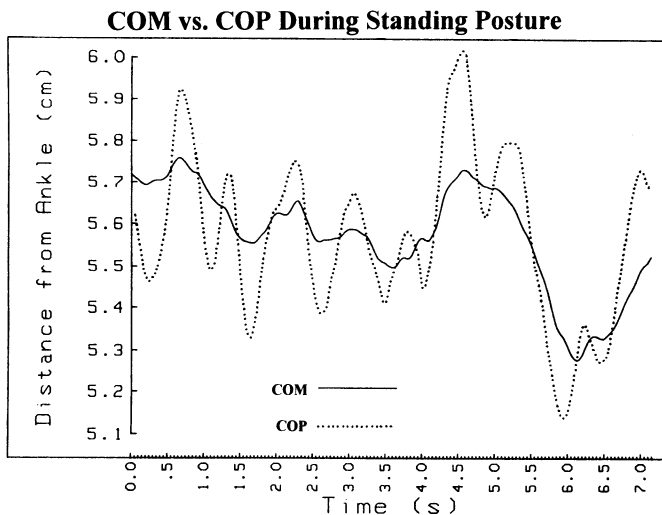


FIG. 2. Seven-second record showing simultaneous COG and center of pressure (COP) fluctuations in the anterior-posterior (A/P) direction for a subject during quiet stance. The controlling COP excursions oscillate to either side of the COG excursions and have higher amplitude and higher frequency.

change. Although we do not estimate the total body COG in this report, we know that its M/L and A/P excursions must be somewhat less than the COP; this has been noted by Winter (1990) and Day et al. (1993).

METHODS

COP measures from two force platforms

With both limbs supported on a single force platform, all we record is the COP_{net} . With two limbs supporting the body on two adjacent force platforms, the COP_{net} in either the A/P or M/L directions is calculated as follows

$$COP_{net}(t) = COP_l(t) \frac{R_{vl}(t)}{R_{vl}(t) + R_{vr}(t)} + COP_r(t) \frac{R_{vr}(t)}{R_{vl}(t) + R_{vr}(t)} \quad (1)$$

where $COP_l(t)$ and $COP_r(t)$ are the COPs under the left and right foot, respectively, and $R_{vl}(t)$ and $R_{vr}(t)$ are the vertical reaction forces under the left and right feet, respectively.

From standard biomechanics analyses (inverse dynamics) it is evident that $COP_l(t)$ and $COP_r(t)$ are entirely under the control of the ankle muscles (Winter 1990). Dorsiflexors and plantarflexors control the A/P movement of these COPs, whereas the ankle invertors/evertors control the M/L movement of these COPs. With the sum of the two vertical forces $\approx 100\%$ body weight, the ratio $\frac{R_{vl}(t)}{R_{vl}(t) + R_{vr}(t)}$ is a

second time-varying control signal reflecting the percent vertical force of the left limb, which usually oscillates around 0.5 when the weight is equally distributed between the left and right feet during quiet stance. The muscle groups that are responsible for the loading of either limb are the hip abductors and adductors (Winter et al. 1993). For example, increased activity of the right hip abductors will attempt to lift the pelvis and the body mass supported by the pelvis and thereby increase the percent vertical force on the right limb and instantaneously decrease the vertical force by the

same amount on the left limb. Figure 3 demonstrates the dynamic changes in these right and left signals during a 16-s record of quiet standing for an adult subject with eyes open. As can be seen, these left and right limb vertical force signals occur completely out of phase, oscillating around 0.5, and the changes over time are not small (the difference between these two signals varied $\sim 10\%$ over this 16-s record). The question arises as to the muscle groups responsible for these fluctuations in R_{vl} and R_{vr} . Unfortunately electromyogram activity of the hip abductors and adductors during quiet standing is subthreshold when compared with these reaction force fluctuations: all we see is low-level myoelectric signals from both abductors and adductors with miniscule fluctuations in activity. However, if we carried out a routine biomechanical analysis (inverse dynamics) we could calculate the frontal plane moments of force at each hip. The shear forces during quiet standing are negligible; thus, as seen in Fig. 3, the hip moment would be the product of the vertical ground reaction force (less the weight of the lower limb) times the horizontal distance from the hip joint center to that vertical force vector. This distance is constant; thus the hip abductor moments show fluctuations identical to $R_{vl}(t)$ and $R_{vr}(t)$. Such a calculation of these moments in quiet standing is therefore redundant but would clearly demonstrate hip abductor/adductor control of the ground reaction forces.

Note that Eq. 1 identifies two separate mechanisms that control COP_{net} . The ankle muscles control COP_l and COP_r , whereas in this side-by-side standing position the hip abductors/adductors control R_{vl} and R_{vr} . Thus we can partition the contribution of each mechanism to the fluctuations of COP_{net}

(Winter et al. 1993) as follows. If we set $\frac{R_{vl}}{R_{vl} + R_{vr}} =$

$0.5 = \frac{R_{vr}}{R_{vl} + R_{vr}}$ we negate the contribution to COP_{net} by the loading/unloading of the limbs. Thus the entire change in COP_{net} will now reflect the contribution from COP_l and COP_r alone. This has been defined as COP_c

$$COP_c(t) = COP_l(t) \cdot 0.5 + COP_r(t) \cdot 0.5 \quad (2)$$

This $COP_c(t)$ is in effect the weighted average of COP_l and COP_r .

If the two limbs do not have exactly the same loading of 50%, each equation is modified to reflect unequal average loads over the assessment period

$$COP_c(t) = COP_l(t) \cdot \bar{R}_{vl} + COP_r(t) \cdot \bar{R}_{vr} \quad (2a)$$

where \bar{R}_{vl} and \bar{R}_{vr} are the average fractional loads carried by the left and right limbs, respectively. In quiet standing $\bar{R}_{vl} = 1 - \bar{R}_{vr}$.

Now, the contribution to COP_{net} due to the load/unload mechanism resulting from the fluctuations in R_{vl} and R_{vr} was defined as $COP_v(t)$, where

$$COP_v(t) = COP_{net}(t) - COP_c(t) \quad (3)$$

Thus our partitioning has separated COP_{net} into two mechanisms, COP_c and COP_v . Although these equations were developed with reference to the side-by-side standing position, they apply to all other standing positions (tandem and all intermediate positions). COP_c and COP_v are referred to

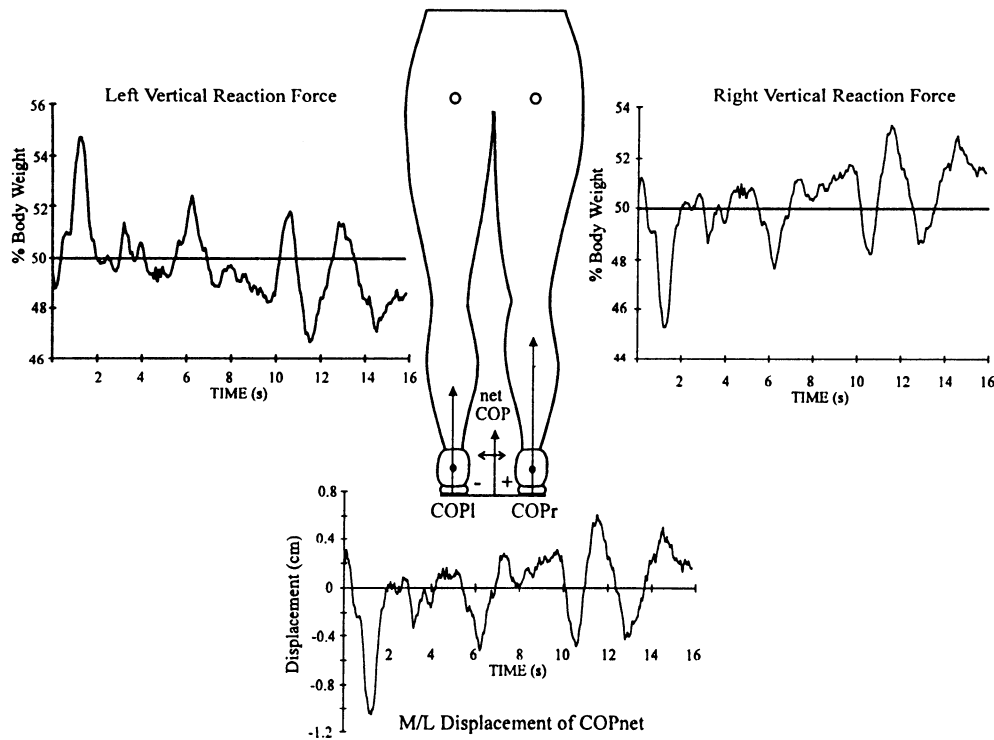


FIG. 3. Dynamic changes in the left and right ground reaction forces expressed as a percentage of body weight while the subject (SK73) is standing for 16 s. These signals oscillate completely out of phase and show quite large fluctuation. *Bottom*: medial-lateral (M/L) displacement of the COP_{net} displacement is in phase with the right vertical reaction force.

as motor control signals because they are the net changes due to the integrated muscle activity that cause COP_c or COP_v to change. We recognize that these motor control signals are ultimately controlled reactively or proactively by the CNS; thus when inferences are made about that control, we refer to neural control and refer to appropriate references in the literature.

Experimental methods

All subjects were young adults averaging 28.7 ± 6.1 (SD) yr of age and 77.9 ± 15.8 (SD) kg in weight, having no known neuromuscular impairment. Subjects stood in each of the positions to get comfortable for ~ 1 min and were instructed to stand as steadily as possible with eyes open.

In the tandem position, subjects had one foot ahead of the other with the lead foot 110% of foot length ahead of the rear foot; the position with right foot ahead was labeled tandem right (TR) and with left foot ahead it was tandem left (TL). With one foot on each force platform, the subject was instructed to partition vertical forces to $\sim 50\%$ of body weight per foot with the use of visual feedback from a meter measuring both vertical force signals. Then the subjects were asked to maintain that position for 16 s with eyes open while the COPs and reaction forces were A/D at 250 Hz. The 45° position was a position in which the leading foot was 110% of foot length ahead of the rear foot and at a comfortable distance to the side. The labeling of this as a 45° position was approximate and varied slightly depending on the M/L distance between the feet that each subject adopted. With the right foot forward the stance position was labeled as 45R; with left foot forward it was 45L. All subjects were tested with arms held naturally at the sides.

Now that the partitioning of the control contributions $COP_v(t)$ and $COP_c(t)$ is established, a technique to quantify how well they

collaborate is needed. A measure of the similarity of any of these COP changes over any given time period can be quantified by a cross-correlation between the COP signals. Such cross-correlations are used routinely to quantify similarity in shape ($R^2 = 1$) or total dissimilarity ($R^2 = 0$) between any two waveforms (Bendat and Piersol 1986). Even a cancellation of two signals when they are completely out of phase will yield an $R^2 = -1$. A high positive correlation means the two variables are acting in phase to contribute to the $COP_{net}(t)$, whereas a high negative correlation means they are canceling to produce a reduced $COP_{net}(t)$. Correlations near 0 are interpreted as no interaction between the two mechanisms. To cross-correlate $COP_v(t)$ with $COP_c(t)$ over the period of time T , we used the following equation

$$R_{vc}(\tau) = \frac{1}{T} \int_0^T COP_c(t) \cdot COP_v(t + \tau) dt \quad (4)$$

where $R_{vc}(\tau)$ is the cross-correlation of $COP_c(t)$ and $COP_v(t)$ at a phase shift τ . Because we are interested in the correlations at the same instant in time, we set $\tau = 0$ and we normalize so that the cross-correlation lies between -1 and $+1$

$$R_{vc}(0) = \frac{1}{T} \int_0^T \frac{COP_c(t) \cdot COP_v(t)}{\sqrt{R_{cc}(0) \cdot R_{vv}(0)}} dt \quad (5)$$

where $R_{cc}(0)$ and $R_{vv}(0)$ are the autocorrelations of COP_c and COP_v , respectively. In a similar manner we can cross-correlate either COP_v or COP_c with COP_{net} to determine how well each mechanism is collaborating to the control of total body balance.

A total of 11 healthy subjects without orthopedic or neurological disorders were tested, and the results of the cross-correlations are presented in Tables 1, 2, and 4. The root-

TABLE 1. Cross-correlation of the contributions to the COP_{net}

Subject	Mediolateral				Anteroposterior			
	COP_c vs. COP_{net}		COP_v vs. COP_{net}		COP_c vs. COP_{net}		COP_v vs. COP_{net}	
	TR	TL	TR	TL	TR	TL	TR	TL
WJ12	0.984	0.994	0.514	0.763	0.529	0.252	0.673	0.945
WJ13	0.987	0.998	0.814	0.902	0.176	-0.059	0.707	0.515
WJ14	0.967	0.984	0.450	0.676	0.584	-0.264	0.584	0.496
WJ15	0.995	0.977	-0.170	-0.709	0.165	-0.384	0.612	0.741
WJ16	1.000	0.940	0.192	0.500	0.034	0.596	0.918	0.804
WJ17	0.993	0.965	0.645	0.237	0.391	0.777	0.466	0.920
WJ20	0.980	0.994	0.047	0.123	0.186	0.302	0.842	0.729
WJ22	0.996	0.997	0.747	-0.228	0.329	0.298	0.186	0.423
WJ40	0.999	0.932	0.113	-0.546	-0.266	-0.490	0.828	0.893
WJ59	0.994	0.986	0.236	0.786	0.220	0.257	0.905	0.732
WJ73	0.999	0.998	0.278	-0.205	0.218	-0.118	0.553	0.868
Average	0.990	0.979	0.351	0.209	0.233	0.106	0.661	0.733
SD	0.010	0.024	0.310	0.566	0.233	0.402	0.217	0.181

COP_{net} , net body center of pressure; TR, tandem right; TL, tandem left. See text for explanation of other variables.

mean-square amplitudes of all the contributions are presented in Table 3.

RESULTS

Tandem stance position

Table 1 presents the cross-correlations between the COP_{net} versus COP_c and COP_v in the M/L and A/P directions for both TR and TL positions. In the M/L direction for both TR and TL positions there are very high correlations (TR = 0.990 ± 0.01 , mean \pm SD; TL = 0.979 ± 0.024 , mean \pm SD) between COP_c and COP_{net} . Such high correlations indicate that the M/L changes in the COPs under the feet are dominant in controlling the COP_{net} . Thus the ankle muscles responsible for the COP changes (ankle invertors/evertors) are dominant in this balance control.

The role of COP_v in this M/L balance is quite variable but very small. For some subjects (i.e., subject WJ13 for TR) this load/unload mechanism is highly correlated (0.814) with the COP_{net} , indicating that it adds to the contribution of COP_c . On others (i.e., subject WJ15 for TL) there is a high negative correlation (-0.709) with the COP_{net} , indicating that it cancels some of the contribution of COP_c . Still others (i.e., subject WK59 for TR) have a small correlation (0.236), indicating a random contribution to COP_{net} (it acts as noise). Despite these widely variable results we note from Table 3 that the magnitude of COP_v is quite small (TR = 0.063 cm, TL = 0.071 cm) compared with the ampli-

tude of COP_c (TR = 0.553 cm, TL = 0.568 cm). Thus the importance of the load/unload mechanism to M/L balance in tandem stance is very minor and that contribution can be additive, subtractive, or random. Figure 4 demonstrates this for one of the subjects (WK59). COP_c plots virtually on top of COP_{net} , whereas $COP_v \approx 0$.

In the A/P direction the results of the balance control are also somewhat mixed. As can be seen from Table 1, for both TR and TL positions the cross-correlations between COP_c and COP_{net} range widely from both positive and negative. Between COP_v and COP_{net} , correlations are moderately high and positive (TR = 0.661 ± 0.217 , mean \pm SD; TL = 0.733 ± 0.181 , mean \pm SD); both were significantly higher than COP_c versus COP_{net} ($P < 0.005$). The amplitudes of COP_v (Table 3) are not significantly different (TR = 0.700 cm; TL = 0.692 cm) than the amplitudes of COP_c (TR = 0.506 cm, TL = 0.496 cm). Although these amplitude differences were not significant, the correlation differences demonstrate the A/P postural control in tandem stance to be dominated by the hip load/unload mechanism. However, for some individual subjects, plantarflexor/dorsiflexor control sometimes reinforced the hip control (i.e., subjects WJ17 and WJ16 for TL position and subject WJ14 for TR position). However, most subjects had relatively low R^2 scores, indicating a negligible contribution of COP_c to COP_{net} . It is noted there were no significant differences in the correlations and amplitudes of COP_v and COP_c between the TR and TL positions.

TABLE 2. Cross-correlation of the contributions to the COP_{net}

	Mediolateral				Anteroposterior			
	COP_c vs. COP_{net}		COP_v vs. COP_{net}		COP_c vs. COP_{net}		COP_v vs. COP_{net}	
	45R	45L	45R	45L	45R	45L	45R	45L
Average	0.945	0.854	0.966	0.938	0.711	0.688	-0.342	-0.283
SD	0.036	0.169	0.036	0.074	0.152	0.238	0.301	0.427

All differences between COP_c and COP_v for the anteroposterior direction are significant ($P < 0.005$). 45R, 45° stance with right foot forward; 45L, 45° stance with left foot forward. See Table 1 for other abbreviations.

TABLE 3. Root mean square of the contributions to the COP_{net}

	Mediolateral						Anteroposterior					
	TR			TL			TR			TL		
	COP_c	COP_v	COP_{net}	COP_c	COP_v	COP_{net}	COP_c	COP_v	COP_{net}	COP_c	COP_v	COP_{net}
Average	0.553	0.063	0.608	0.568	0.071	0.596	0.506	0.700	0.576	0.496	0.692	0.490
SD	0.254	0.103	0.317	0.265	0.034	0.286	0.536	0.744	0.594	0.322	0.382	0.188
	Mediolateral						Anteroposterior					
	45R			45L			45R			45L		
	COP_c	COP_v	COP_{net}	COP_c	COP_v	COP_{net}	COP_c	COP_v	COP_{net}	COP_c	COP_v	COP_{net}
Average	0.215	0.319	0.506	0.212	0.390	0.557	0.732	0.536	0.321	0.842	0.624	0.392
SD	0.072	0.125	0.128	0.067	0.116	0.172	0.229	0.171	0.108	0.282	0.222	0.133

Values are in cm. For TR and TL, all differences between COP_c and COP_v for the mediolateral direction are significant ($P < 0.005$). For 45R and 45L, all differences between COP_c and COP_v significant at $P < 0.05$ except the mediolateral direction at 45L ($P < 0.005$). For abbreviations, see Tables 1 and 2.

45° stance position

Table 2 presents the cross-correlations between the COP_{net} versus COP_c and COP_v in the M/L and A/P directions for both 45R and 45L positions. In the M/L direction for both 45R and 45L positions, there are very high correlations between COP_v and COP_{net} (45R = 0.966 ± 0.036 , mean \pm SD; 45L = 0.938 ± 0.074 , mean \pm SD). Again, regarding these high correlations and their moderately high amplitudes, Table 3 (45R = 0.319 cm; 45L = 0.390 cm) indicates that the M/L control of posture (COP_{net}) is dominated by the hip load/unload mechanism, COP_v . The role of COP_c in this M/L control is also seen to be quite important. There are very high correlations (Table 2) between COP_c and COP_{net} (45R = 0.945 ± 0.036 , mean \pm SD; 45L = 0.854 ± 0.169 , mean \pm SD), but the average amplitudes of the contributions were $\sim 60\%$ of the COP_v contributions (45R = 0.215 cm; 45L = 0.212 cm). To demonstrate this collaboration between these two mechanisms, we show in Fig. 5 that COP_c and COP_v are in phase with each other and that COP_v for this subject (WK73) has about the same amplitude as COP_c ;

thus each contributes equally to COP_{net} to control M/L body balance.

In the A/P direction we see a different control strategy for both 45R and 45L positions. Table 2 reports a moderately high and positive correlation between COP_c and COP_{net} (45R = 0.711 ± 0.152 , mean \pm SD; 45L = 0.688 ± 0.238 , mean \pm SD) with large amplitudes (45R = 0.732 cm; 45L = 0.842 cm). On the other hand, the correlation between COP_v and COP_{net} is negative and quite small (45R = -0.342 ± 0.301 , mean \pm SD; 45L = -0.283 ± 0.427 , mean \pm SD) and the amplitude is also high (45R = 0.536 cm; 45L = 0.624 cm). More importantly, the correlation between COP_c and COP_v (Table 4) is large and negative (45R = -0.886 ± 0.108 , mean \pm SD; 45L = 0.853 ± 0.193 , mean \pm SD). Thus the total control of COP_{net} appears to be a cancellation, because the amplitude of the desired COP_{net} (45R = 0.321 cm; 45L = 0.392 cm) is much smaller than either COP_v or COP_c . We are reminded that the same hip load/unload mechanism is involved in both A/P and M/L balance. In the M/L direction, the COP_v and COP_c were both in phase with the COP_{net} . However, this same

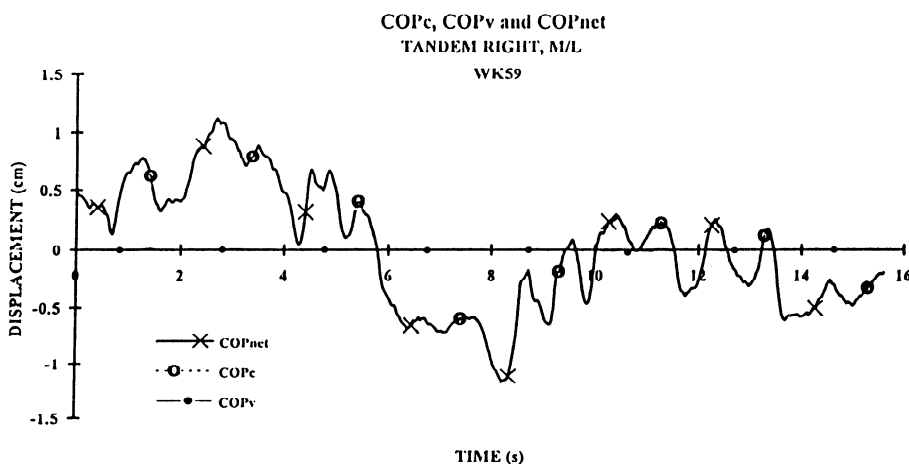


FIG. 4. Partitioning of the COP_{net} in the M/L direction for subject WK59 standing in the tandem position with right foot forward over a 16-s period. The COP_{net} (dark solid line with \times) is almost 100% dominated by the ankle mechanism, COP_c , with minuscule contribution from the hip load/unload mechanism, COP_v (light solid line with \bullet). COP_c (\dots with \circ) is not apparent because it is virtually the same as COP_{net} .

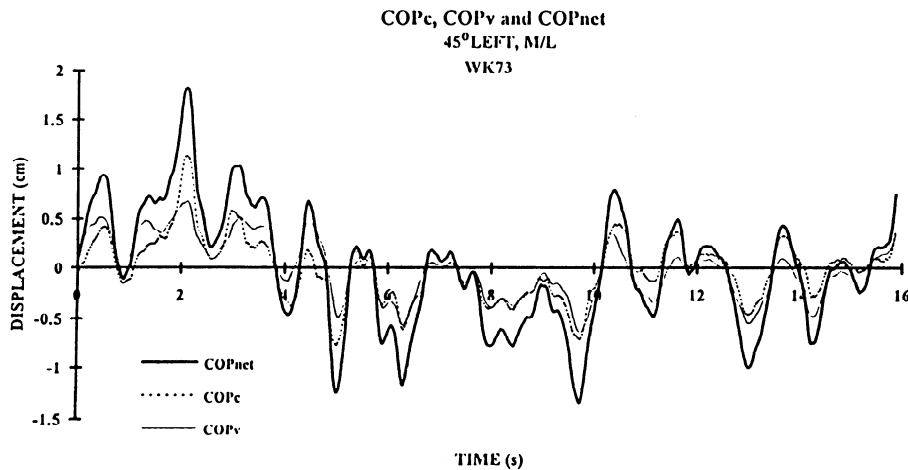


FIG. 5. Partitioning of the COP_{net} in the M/L direction for *subject WK73* standing in the 45L position over a 16-s period. Both ankle and hip mechanisms collaborate by adding to produce the desired COP_{net} fluctuations.

COP_v load/unload response in the A/P direction is inappropriate (it is far too large and is not even in phase with the desired COP_{net}). Thus the ankle motor response of dorsiflexors/plantarflexors must intervene to subtract from the inappropriate COP_v in order to achieve the desired COP_{net} . Figure 6 demonstrates this subtraction process for the same subject (*WK73*) where COP_c and COP_v are both large ($COP_c = 0.772$ cm, $COP_v = 0.742$ cm) and virtually out of phase. Thus COP_c subtracts from COP_v to yield a much smaller ($COP_{net} = 0.265$ cm) and appropriate COP_{net} .

It is noted that there were no significant differences in the correlations and amplitudes of COP_v and COP_c between the 45R and 45L positions.

DISCUSSION

In terms of our original hypotheses, we were only partially correct. The complexity and combination of control mechanisms was not as simple as we originally predicted.

For tandem stance, our predictions of ankle control being dominant in M/L balance were correct, and this was based on the fact that the ankle inverter/evertor joints were lined up and the width of the base of support was small. We did not predict any contribution by the hip load/unload mechanism;

however, a small and variable contribution was evident. Sometimes it was additive, sometimes subtractive, and sometimes random. In the A/P direction for tandem stance, we predicted a dominant hip load/unload response, and that was evident. Again, the ankle mechanism sometimes reinforced, and sometimes subtracted, but most subjects demonstrated negligible contribution.

For the 45° stance position, we hypothesized that there would be significant contributions from both ankle and hip mechanisms. We were correct, but we assumed those contributions would be additive. In the M/L direction, both COP_v and COP_c reinforced to contribute to COP_{net} with the greater contribution (60%) coming from the load/unload mechanism and 40% from the ankle muscles. Because this hip load/unload mechanism is applied to control both M/L and A/P balance, we see that what is appropriate in the M/L direction is not appropriate in the A/P direction. Therefore the ankle muscles intervene and respond with a large control to subtract from COP_v to yield a much smaller and correct COP_{net} .

To integrate the findings of these two positions with those from the original side-by-side position, we present Figs. 7 and 8. Figure 7 plots COP_{net} , COP_c , and COP_v for a subject standing in the side-by-side position. As can be seen, the

TABLE 4. Cross-correlation of the COP_c and COP_v .

Subject	Mediolateral				Anteroposterior			
	TR	TL	45R	45L	TR	TL	45R	45L
WJ12	0.453	0.699	0.886	0.669	-0.253	-0.088	-0.934	-0.890
WJ13	0.711	0.874	0.975	0.954	-0.572	-0.886	-0.983	-0.951
WJ14	0.473	0.575	0.975	0.918	-0.618	-0.970	-0.983	-0.922
WJ15	-0.216	-0.745	0.750	0.853	-0.670	-0.870	-0.760	-0.945
WJ16	0.151	0.395	0.904	0.866	-0.307	0.061	-0.942	-0.851
WJ17	0.606	0.122	0.806	0.362	-0.644	0.501	-0.849	-0.940
WJ20	-0.155	0.013	0.750	0.499	-0.374	-0.433	-0.851	-0.733
WJ22	0.688	-0.299	0.732	0.881	-0.867	-0.739	-0.959	-0.918
WJ40	0.097	-0.615	0.933	-0.193	-0.752	-0.826	-0.915	-0.309
WJ59	0.227	0.691	0.954	0.906	-0.221	-0.464	-0.939	-0.984
WJ73	0.220	-0.280	0.615	0.853	-0.692	-0.613	-0.631	-0.939
Average	0.296	0.130	0.843	0.688	-0.543	0.484	-0.886	-0.853
SD	0.319	0.561	0.120	0.348	0.218	0.466	0.108	0.193

For abbreviations, see Tables 1 and 2.

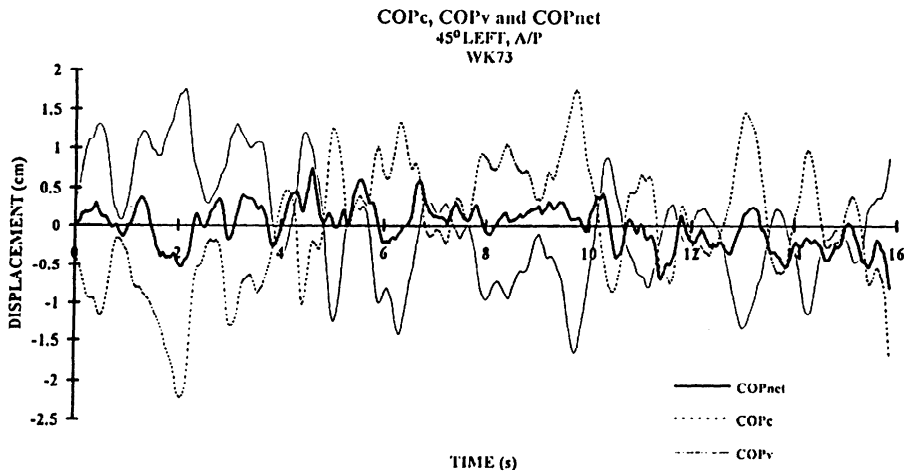


FIG. 6. Partitioning of the COP_{net} in the A/P direction for the same subject and trial as in Fig. 5. The hip and ankle mechanisms are almost out of phase, indicating a subtractive collaboration to produce the desired COP_{net}. See text for the neurological implications of this complex and simultaneous collaboration as demonstrated by Figs. 5 and 6.

COP_v contribution lies along a straight line joining the individual COPs under each foot. This load/unload line may not be perfectly in the M/L direction, as shown here, because the COP_l was slightly anterior of the COP_r, meaning the left plantarflexor moment was biased slightly higher than the right. Almost 90° from this load/unload line is the COP_c line representing the net control of the plantarflexors/dorsiflexors. These two independent controls then sum in time and space to yield the random-looking COP_{net} (which is what would be recorded from a single force platform). Figure 8 shows the same spatial plots for the right foot 45° ahead of the left. As before, the COP_v line is a straight line joining the locations of COP_l and COP_r. In this case the COP_c changes controlled by the ankle muscles move back and forth along a line ~60° from the COP_v load/unload line. Thus these mechanisms are separate but not independent. Again the random COP_{net} plot is the spatial and temporal summation of these two COP_v and COP_c lines. The fact that COP_c moves forward to the left and backward to the right means that the controlling ankle muscles include the right peroneii (whose

activation will cause the COP to move forward to the left) and right tibialis anterior (whose activation will cause the COP to move backward to the right). Some of these COP changes could also be caused by the left tibialis posterior (whose action would cause the COP to move forward and to the left). In terms of what muscles could be controlling the COP_v line to load/unload the two hip joints, we would interpret that the left abductors/extensors acting together would cause COP_v to move backward and to the left. Or, the right abductors/flexors could cause COP_v to move forward and to the right.

Finally, Fig. 9 integrates the nominal responses for all three positions to demonstrate that the COP_v hip control always lies along a line joining the two COPs under each foot, whereas the ankle COP_c mechanism is at an angle from the COP_v. In the side-by-side position this angle averaged 89 ± 4.0° (mean ± SD), indicating each mechanism acts independently of each other. In the tandem position they

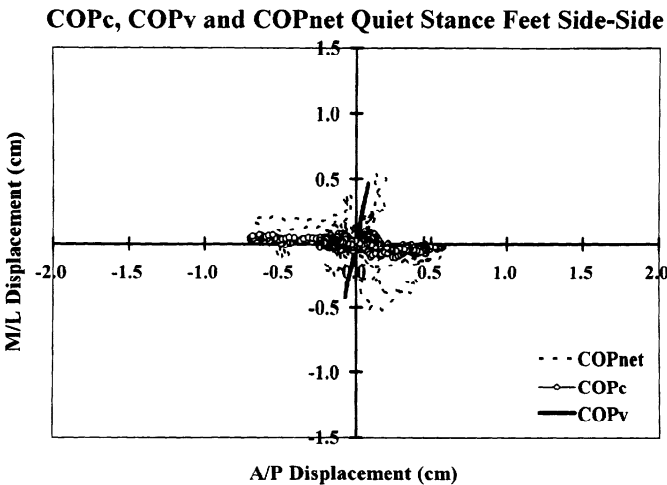


FIG. 7. Trajectory of COP_{net} in M/L and A/P directions for a subject standing with feet side by side. COP_{net} is partitioned into its 2 separate components, COP_v and COP_c. COP_v, the load/unload line, acts along a line joining the COPs under each foot, whereas COP_c acts almost 90° from the COP_v line. Thus the 2 separate mechanisms are also independent in this position.

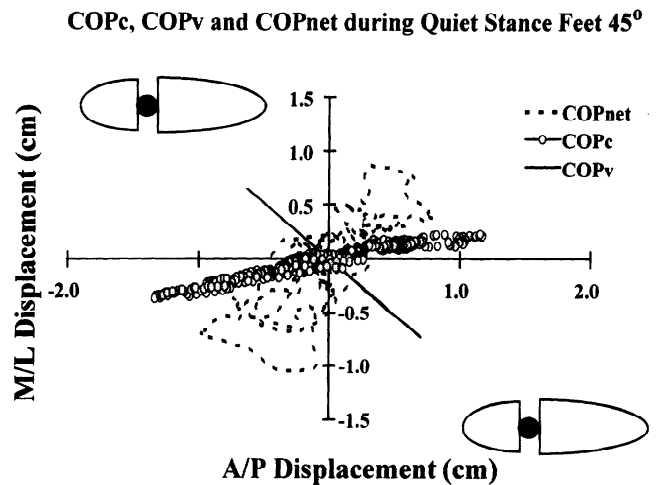


FIG. 8. Trajectories of COP_{net}, COP_v, and COP_c for a subject standing quietly with the right foot 45° ahead of the left. Partitioning of the 2 mechanisms shows the COP_v load/unload line to act along a line joining the COPs under each foot, whereas the COP_c line controlled by the ankle muscles acts at 60° from the COP_v line. The scale for the COPs is exaggerated relative to the foot positions in order to make visible their lines of action. See text for discussion regarding the collaboration of these separate mechanisms.

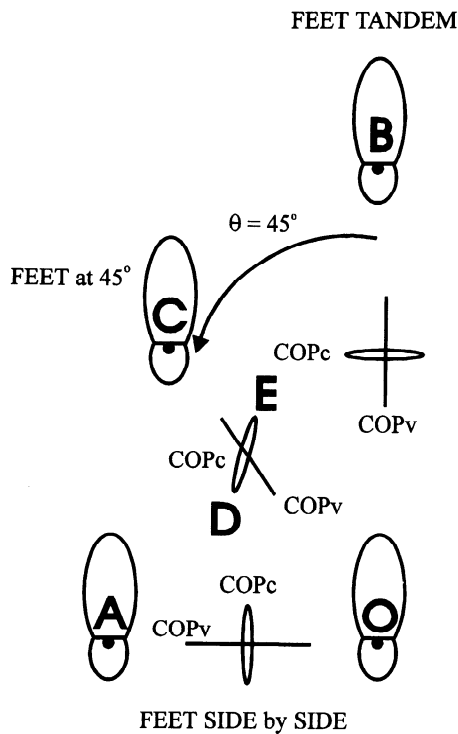


FIG. 9. Summary of the trajectories of the separate mechanisms in all 3 stance positions. The COP_v load/unload line always acts along a line joining the individual COPs under each foot, whereas the COP_c controlled by the ankle muscles acts at 90° (side by side and tandem) or at an angle $<90^\circ$ in the intermediate positions. In the side-by-side positions the mechanisms are independent; in intermediate positions there must be collaboration between the hip and ankle mechanisms.

would be $\sim 90^\circ$ from each other if each ankle's invertors/evertors exerted equal control. However, because the axes of the subtalar joints of each foot are not the same in this tandem position, the angle of COP_c was somewhat variable depending on which foot dominated control of M/L balance. For the TR position, the angle between COP_v and COP_c averaged 81° but had high variability ($\pm 31^\circ$, mean \pm SD). For the TL standing position, the angle between COP_v and COP_c averaged 77° , again with a high standard deviation ($\pm 29.7^\circ$). The intermediate 45R and 45L positions were very consistent. The angle between COP_c and COP_v for 45R averaged $49.4 \pm 4.7^\circ$ (mean \pm SD), whereas for the 45L stance the angle between COP_c and COP_v averaged $45.6 \pm 7.6^\circ$ (mean \pm SD). Thus in these intermediate positions these separate ankle and hip mechanisms are not independent and must collaborate with each other. As was evident from the correlation analyses, both mechanisms collaborated in the M/L direction by a partial reinforcement and in the A/P direction with a partial cancellation. Day et al. (1993) reported that M/L COP and eight markers tracked with an image analysis system showed that a wider stance was more stable. Such a finding would be predicted from Eq. 1, where the load/unload mechanism controls the percentage COP change between the two feet. For feet spaced 40 cm apart, a 2% change in R_{v1} and R_{v2} would cause a 2% shift in the M/L COP, which would be 0.8 cm. However, with a 10-cm spacing, R_{v1} and R_{v2} would have to change by 8% to cause an 0.8-cm change in the COP. Thus our inverted pen-

dulum model would predict that wider stances require proportionately less hip abductor/adductor activity to maintain the same COP control.

In the assessment of balance in patients with cerebellar disease, Diener et al. (1984) and Lucy and Haycs (1985) reported greater COP excursions while patients stood in the side-by-side position with eyes open and with eyes closed. In this position the M/L and A/P control are separate mechanisms (Winter et al. 1993), and therefore the potential conflict in the cerebellum may not be seriously challenged. However, the 45° position is far more challenging to the collaboration between these two mechanisms, and therefore loss of this coordination in cerebellar and hemiplegic patients may be made more evident by analyzing their balance with two force platforms and having them adopt the 45° position. Also, this 45° position is fairly close to the position during the double support phase of walking, when patients with short step lengths rebalance themselves over the stride period.

Researchers who have adopted the tandem position for their subjects or patients have done so to achieve a more challenging task (cf. Black et al. 1982). For that position, this report demonstrates an ankle strategy in the M/L direction and a dominant hip load/unload strategy in the A/P direction. Thus in patient studies it would be important to know not only that the COP_{net} in either direction was increasing but also which of the two mechanism was degenerating.

These findings demonstrate that balance control even during quiet standing is not a simple single motor control pattern but is a collaborative effort between two independent motor groups. Also, studies of balance need to be expanded from A/P responses (cf. McCollum and Leen 1989) to the combined responses in both A/P and M/L directions. Macpherson (1988) has already commented on collaboration between hip and ankle muscles for cats in response to A/P perturbations. The clinical significance of such findings is important in evaluating the balance control of many patient populations: below-knee amputees who may have lost ankle control in one or both ankles, stroke patients who have lost unilateral control of both ankle and hip muscles, paraplegic patients being assessed for functional electrical stimulation control, peripheral neuropathy patients, etc. In these situations, by partitioning COP_v and COP_c we would be able to identify the site of the muscle groups responsible for increased COP changes. Also, the 45° position is a dramatic demonstration of complex collaboration between these separate motor strategies. The cerebellum could serve to coordinate these separate motor strategies, because lesions of the vermis and intermediate regions cause severe postural ataxia (Dichgans and Fetter 1993; Diener et al. 1994). Cerebellar patients fail to properly scale the duration and magnitude of muscle responses to maintain upright stance (Horak and Diener 1994). Thus neural disorders in the cerebellum would be predicted to exhibit major conflicts between these two mechanisms. The role of these balance mechanisms is also important in the study of falls in the elderly. A loss of balance in the lateral direction would be especially difficult to recover from, because the unloaded limb is on the opposite side from the direction of fall, whereas in the A/P directions a corrective step forward or backward is possible.

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Address for reprint requests: D. A. Winter, Dept. of Kinesiology, University of Waterloo, Waterloo, Ontario N2L 3G1, Canada.

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