Medial-lateral and anterior-posterior motor responses associated with centre of pressure changes in quiet standing

Article *in* Neuroscience Research Communications · January 1993

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MEDIAL-LATERAL AND ANTERIOR-POSTERIOR MOTOR RESPONSES ASSOCIATED WITH CENTRE OF PRESSURE CHANGES IN QUIET STANDING

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(Accepted March 22, 1993)

SUMMARY

In quiet standing with feet side by side the motor control sites were investigated in the anterior/posterior (A/P) and medial/lateral (M/L) directions. In the A/P direction the left and right limb center of pressure *(COP)* changes were quite synchronized while in the M/L direction they were antiphase. In the A/P direction the total body net *COP* changes were virtually 100% controlled by the right and left *COP* changes. However, in the M/L direction the right and left *COP* changes contributed almost nothing to the net *COP* changes. Rather, the M/L postural control was dominated by a loading/unloading response. Thus the ankle strategy in postural control in this natural standing condition is limited to the A/P direction. Based on a closed link kinematic chain we would postulate this M/L loading/unloading control to be under the control of the hip abductors/adductors.

KEY WORDS: Postural control, Quiet stance, Medial-Lateral and Anterior-Posterior responses

INTRODUCTION

The primary variable that has been recorded to document the net postural and balance responses during standing has been the net body centre of pressure (net *COP*) recorded from single force platforms[1]. The net *COP* is the integrated control variable while the body's centre of mass *(COM)* is the controlled variable. In an inverted pendulum model of standing balance[1] the motor system was modelled as two torque motors at the ankle. The vertical projection of the *COM* is the centre of gravity *(COG)* has been compared with the net *COP* to demonstrate the essential difference between the controlled variable and the controlling variable[1,2]. Some researchers have treated the model to be the same in both A/P and M/L directions[1] while others have referred to the net *COP* fluctuations both A/P and M/L direction to be a stability cone[3]

0893–6609/93/030141–08$09.00

or to be the result of contractions and relaxations of the "supporting muscles"[4]. Sagittal plane muscles at the ankle, knee, hip and trunk have been monitored by many groups and a general postural strategy, called ankle and hip strategy[5] has become a widely accepted planar A/P response for everthing from quiet stance to severely perturbed standing. Nothing other than net *COP* changes has been reported in the M/L direction; motor strategies at the various joints have not been investigated.

THEORY AND METHODS

In single limb standing there is no doubt that the ankle muscles are the final controller to keep the *COG* within the small base of support. The (A/P) trajectory of the net *COP* reflects the net dorsiflexor/plantarflexor motor response while the (M/L) movement of the net *COP* reflects the net inversion/eversion ankle responses. However, during normal double limb standing such an assumption is not true, and this is because the *COP* is the net response of both limbs. Such a response is not evident until we are forced to calculate the net *COP* from the individual responses under each foot. The net *COP* in either the A/P or M/L directions is calculated as follows:

$$net\ COP(t) = COP_l(t)\ \frac{R_{vl}(t)}{R_{vl}(t) + R_{vr}(t)} + COP_r(t)\ \frac{R_{vr}(t)}{R_{vl}(t) + R_{vr}(t)} \qquad Eqtn.1$$

where: $COP_l(t)$ and $COP_r(t)$ are the *COP's* under the left and right feet respectively.

$R_{vl}(t)$ and $R_{vr}(t)$ are the vertical reaction forces under the left and right feet respectively. Equation 1 focuses on the fact that the net *COP* in either direction is under the control of four time-varying variables, each of which is under the control of a different set of muscles. In the M/L direction, for example, $COP_l(t)$ is under the control of the left ankle inverters/evertors, $COP_r(t)$ is under the control of the right ankle invertors/evertors. $R_{vl}(t)$ and $R_{vr}(t)$ are the loadings under each foot and when expressed as a time-varying fraction of total body weight, $R_{vl}(t) + R_{vr}(t)$, these fractions represent the dynamically changing loadings under each foot. The purpose of this paper is twofold: (i) to document the relative synchronization between the right and left ankle motor control in both A/P and M/L directions; (ii) to document the relative contribution of these two separate mechanisms: ankle motor control vs limb loading/unloading control in both the M/L and A/P directions.

Equation 1 documents the total response of each limb to the net *COP*. If we are equally supported by the left and right limbs the fraction of the total body weight will be equal to 0.5:

$$\frac{R_{vl}(t)}{R_{vl}(t) + R_{vr}(t)} = \frac{R_{vr}(t)}{R_{vl}(t) + R_{vr}(t)} = 0.5 \qquad Eqtn.2$$

Thus if there is no loading/unloading dynamic response in equation 1 we can set these fractions to 0.5 to isolate the response due to right and left *COP* changes alone, $COP_c(t)$:

$$COP_c(t) = COP_l(t) \cdot 0.5 + COP_r(t) \cdot 0.5 \qquad Eqtn.3$$

This $COP_c(t)$ is in effect the average of COP_l and COP_r. Then if we subtract the COP_c contribution from the net *COP* we can determine the loading/unloading contribution due to the vertical reaction forces:

Ten subjects were analysed while standing quietly with each foot separated about 20 cm on two adjacent force platforms (AMTI Corporation) and with each foot aligned in the sagittal

$$COP_v(t) = net\ COP(t) - COP_c(t) \qquad Eqtn.4$$

plane. Sixteen seconds of data were collected at 250Hz for two trials for each subject, one with eyes open, the other with eyes closed. Net $COP(t)$, $COP_c(t)$ and $COP_v(t)$ were calculated as per Eqtns. 1, 3 and 4 in both the A/P and M/L directions. A measure of the average contribution of $COP_c(t)$ and $COP_v(t)$ to the net COP(t) over the 16 second period was calculated from the root mean square of each of these three time-varying signals:

$$ie.\ \overline{COP} = \sqrt{\frac{1}{16}\int_0^{16} COP^2(t)\, dt} \qquad Eqtn.5$$

A measure of the dependence or independence of these left and right centres of pressure can be determined by a cross-correlation between $COP_l(t)$ and $COP_r(t)$.

$$R_{lr}(\tau) = \frac{1}{T}\int_0^T COP_l(t) \cdot COP_r(t+\tau)\, d\tau \qquad Eqtn.6$$

where: $R_{lr}(\tau)$ is the cross correlation between $COP_l(t)$ and $COP_r(t)$ at any phase shift τ.

Because we are interested in contributions at the same point in time we calculate the cross correlations at $\tau = 0$ and we normalize so that the cross correlation will lie between -1 and +1:

$$R_{lr}(o) = \frac{1}{T}\int_0^T \frac{COP_l(t) \cdot COP_r(t)}{\sqrt{R_{ll}(o) \cdot R_{rr}(o)}}\, dt \qquad Eqtn.7$$

where: $R_{ll}(o)$ and $R_{rr}(o)$ is the autocorrelation of COP_l and COP_r respectively.
In a similar manner we also calculate the dependence between the two separate mechanism as reflected in $COP_c(t)$ versus $COP_v(t)$.

RESULTS

One representative subject trial (WK73) is reported in detail and the results of the relative contributions of COP_c and COP_v and the correlations of all subjects are tabulated for the M/L and A/P directions in Tables 1, 2 and 3.

Figure 1 shows the left and right foot vertical ground reaction forces expressed as a fraction

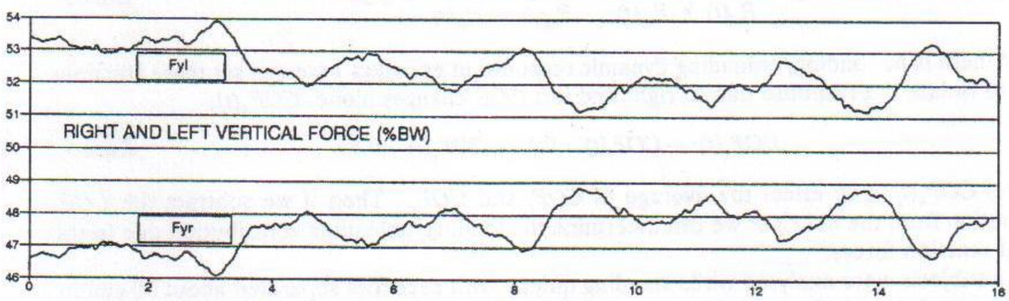

Figure 1. Right and left vertical forces (%BW) over 16 second of quiet stance with eyes closed.

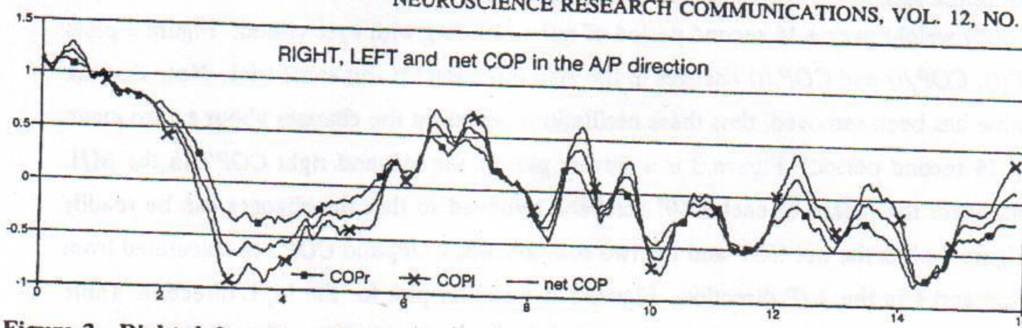

Figure 2. Right, left and net COP (cm) in A/P direction for same trial as Figure 1.

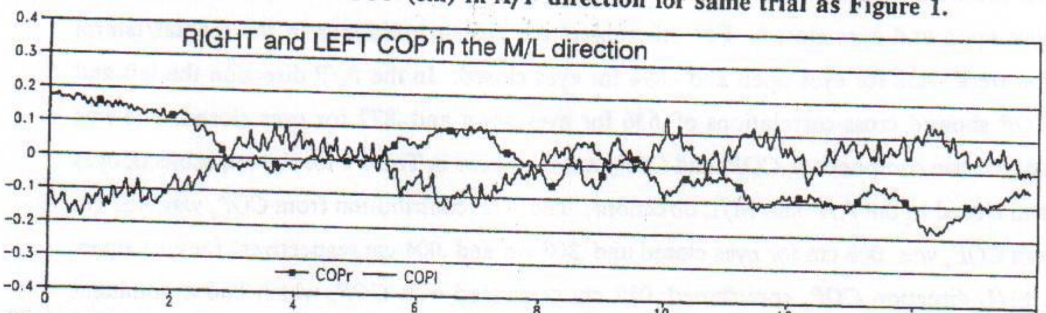

Figure 3. Right and left COP (cm) in M/L direction for same trial as Figure 1.

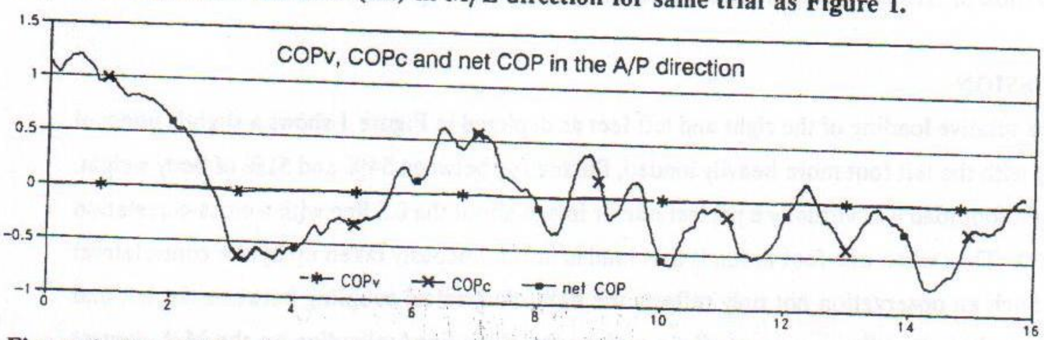

Figure 4. Net COP and two components, COP_c and COP_v in A/P direction.

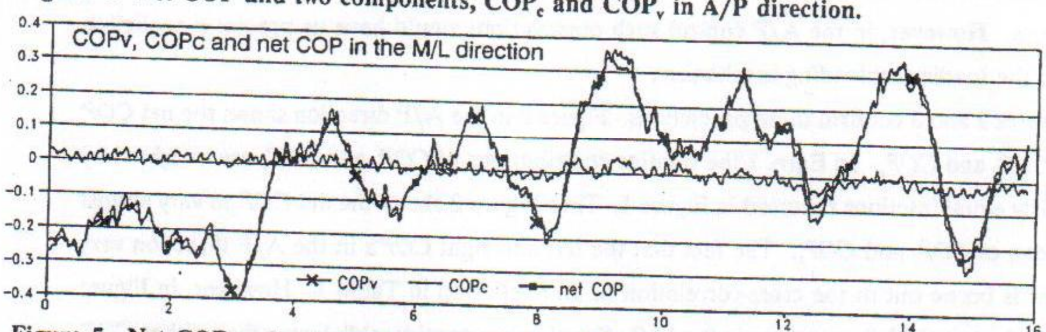

Figure 5. Net COP and two components, COP_c and COP_v in M/L direction.

of total body weight over a 16 second period of quiet standing with eyes closed. Figure 2 plots net $COP(t)$, $COP_l(t)$ and $COP_r(t)$ changes in the A/P direction for this same trial. Note that the mean value has been removed, thus these oscillations represent the changes about a zero mean over the 16 second period. Figure 3 is a similar plot of the left and right *COP's* in the M/L direction; again the means of each *COP* has been removed so that the changes can be readily seen. Figure 4 plots the net COP and the two components, COP_c and COP_v, as calculated from Eqtns. 1, 3 and 4 in the A/P direction. Figure 5 is a similar plot for the M/L direction. Table 1 reports the cross-correlations between the individual *COP's* in the M/L and A/P directions for both eyes open and eyes closed. For this subject the cross-correlations in the medial/lateral direction were -.432 for eyes open and -.894 for eyes closed. In the A/P direction the left and right *COP* showed cross-correlations of .636 for eyes open and .877 for eyes closed. The rms values of the two components, COP_c and COP_v, are tabulated in Table 2 for the ten subjects, eyes open and closed in the A/P and M/L directions. The A/P contribution from COP_c was .482 cm and from COP_v was .008 cm for eyes closed and .308 cm and .004 cm respectively for eyes open. In the M/L direction COP_c contributed .019 cm compared with COP_v which had a dominant contribution of .178 cm for eyes closed, and for eyes open COP_c was .037 cm versus .164 cm for COP_v.

DISCUSSION

The relative loading of the right and left feet as depicted in Figure 1 shows a slightly unequal loading with the left foot more heavily loaded, fluctuating between 54% and 51% of body weight. The right foot load was virtually a perfect mirror image about the 0.5 line with a cross-correlation of -1.000. Thus when one foot unloads that load is instantaneously taken up by the contralateral limb. Such an observation not only reflects the tight mechanical coupling between the left and right limbs but also allows us to predict a major role of loading/unloading on the M/L control of posture. However, in the A/P control such observations would have us predict a negligible role for the loading/unloading mechanism.

Figures 2 and 3 confirm these predictions. Figure 2 in the A/P direction shows the net *COP* vs the COP_l and COP_r. In Eqtn. 1 the relative contributions of COP_l and COP_r are weighted by the nearly equal fractions reported in Figure 1. Thus Figure 2 shows the net *COP* to vary almost as a mean of COP_l and COP_r. The fact that the left and right *COP's* in the A/P direction vary together is borne out in the cross-correlation of .877 reported in Table 1. However, in Figure 5 we see the net *COP* fluctuations in the M/L direction are considerably larger than either COP_l or COP_r. Also, the polarity fluctuations in the COP_l appear to be out of phase with those in COP_r

Table 1. Cross-Correlation of COP_l & COP_r

	M/L		A/P	
	OPEN	CLOSED	OPEN	CLOSED
WJ11	-0.904	-0.734	0.923	0.922
WJ12	-0.590	-0.765	0.586	0.737
WJ13	-0.783	-0.936	0.845	0.990
WJ14	-0.639	-0.363	0.765	0.793
WK31	-0.726	-0.805	0.834	0.760
WK40	-0.448	-0.621	0.687	0.777
WK73	-0.432	-0.894	0.636	0.877
WJ15	-0.874	-0.911	0.976	0.975
WJ16	-0.626	-0.462	0.816	0.924
WK59	-0.801	-0.893	0.887	0.845
aver	-0.682	-0.738	0.795	0.860
stdev	0.164	0.198	0.126	0.091

Table 3. Cross-Correlation of COP_c & COP_v

	M/L		A/P	
	OPEN	CLOSED	OPEN	CLOSED
WJ11	-0.587	0.680	-0.870	0.649
WJ12	-0.626	0.064	0.650	0.500
WJ13	-0.105	-0.530	0.063	0.906
WJ14	0.150	0.087	-0.908	-0.452
WK31	-0.514	0.194	0.534	0.275
WK40	0.293	0.183	-0.062	-0.321
WK73	-0.124	0.008	0.624	0.189
WJ15	0.171	0.173	0.190	0.310
WJ16	0.383	0.334	-0.711	-0.585
WK59	0.935	0.801	0.112	-0.152
aver	-0.002	0.199	-0.038	0.132
stdev	0.493	0.367	0.599	0.494

Table 2 R.M.S. (cm) of COP contributions over 16 seconds

	M/L				A/P			
	OPEN		CLOSED		OPEN		CLOSED	
	COP_c	COP_v	COP_c	COP_v	COP_c	COP_v	COP_c	COP_v
WJ11	0.021	0.093	0.030	0.251	0.305	0.005	0.311	0.030
WJ12	0.036	0.299	0.068	0.235	0.314	0.030	0.452	0.013
WJ13	0.021	0.116	0.037	0.282	0.408	0.018	1.540	0.037
WJ14	0.028	0.086	0.044	0.099	0.507	0.011	0.306	0.006
WJ31	0.107	0.237	0.044	0.289	0.739	0.027	0.488	0.024
WK40	0.019	0.241	0.040	0.256	0.225	0.017	0.433	0.037
WK73	0.037	0.164	0.019	0.179	0.308	0.004	0.482	0.008
WJ15	0.028	0.058	0.030	0.127	0.258	0.001	0.309	0.001
WJ16	0.018	0.048	0.039	0.164	0.220	0.005	0.507	0.007
WK59	0.049	0.171	0.036	0.189	0.349	0.016	0.468	0.017
aver	0.036	0.151	0.039	0.207	0.363	0.013	0.530	0.018
stdev	0.027	0.086	0.013	0.065	0.158	0.010	0.364	0.013

indicating an anti-phase change in individual *COP's* which by themselves would tend to cancel out; a medial change in the left foot due to increased eversion motor activity is matched by somewhat similar eversion motor activity on the right foot, and vice versa. A measure of these anti-phase changes in COP_l and COP_r is reported in the cross-correlation of -.894 in Table 1. Therefore it is evident from Figure 3 that the dominant contribution to the M/L net *COP* changes is not due to the individual ankle invertors/evertors but rather due to the loading/unloading motor response. Similar correlations have been attempted between the A/P and M/L shear forces and the resultant A/P and M/L center of pressure changes but the correlations were low[5]. However, such results are not too surprising because *COP* displacements are the second time-integral of the shear reaction forces.

The relative contributions of the individual *COP* changes versus the loading/unloading contributions is evident in Figures 4 and 5. In the A/P direction (Fig. 4) the contribution from the left and right *COP* changes is almost total with negligible contribution from the loading/unloading mechanism. This dominance of the plantarflexors/dorsiflexor motor control is not surprising when we consider that the axes of the ankle joints are aligned symmetrically and that the individual *COP* changes in the A/P direction are closely synchronized. Thus any fluctuations in sharing of load between the left and right feet will have little influence on the net *COP* in the A/P direction. However, in the M/L direction the opposite control strategy exists. Figure 5 shows the dominance of the COP_v which is virtually equal to the net *COP*. The *COP* contribution from the left and right feet is negligible. In fact, the correlation (Table 3) between this minuscule COP_c contribution versus the dominant loading/unloading contribution was .008. Thus the COP_c contribution was not even correlated with the net *COP* changes and had no net influence on the control of M/L postural control. The major question now arises as to the site or sites of the loading/unloading. It is obvious that the ankle invertors/evertors are not involved so it appears that the loading/unloading must be more proximal. The knee muscles can generally be discounted because they are dominantly A/P muscles. Thus the hip muscles, specifically abductor/adductors, are the ones that have the potential to control loading/unloading. For example, increased abductor activity on the right hip will unload the left limb and the weight will automatically be transferred through tight mechanical coupling to the right limb. Recently, Geurts and Mulder[6] have commented on the potential for postural control of this "four bar closed kinematic chain" by the abductors and adductors of the hip.

A summary of the results for the other subjects is seen in the three tables. As can be seen from Table 1 the left and right *COP's* in the A/P direction were highly and positively correlated indicating synergistic motor patterns of the ankle plantarflexors and dorsiflexors in the left and right limbs. Conversely, in the M/L direction the left and right *COP's* were strongly negatively correlated indicating that they were tending to cancel out their contributions to the net *COP*. The magnitude of these negative correlations was slightly lower than that seen in the A/P direction. Also, the magnitude of the correlations for the eyes-closed condition was slightly larger than for the eyes-open condition. We might speculate that the loss of visual feedback in the eyes-closed condition resulted in an increased reliance on peripheral proprioception resulting in an increased synergy between the left and right motor patterns.

Table 2 summarized the relative magnitudes of the COP_v versus the COP_c mechanisms in controlling the net *COP*. For the A/P direction COP_c is dominant by a factor of about 20 times that of COP_v which reinforces the conclusion by all researchers that A/P posture is under the control of the ankle dorsiflexors/plantarflexors. Conversely, in the M/L direction the COP_v dominates but by a somewhat smaller factor. This finding is total contrary to inferences (in most cases, implied) by previous researchers that the M/L control of posture is also the responsibility of the ankle muscles (invertors/evertors). Loading/unloading is the dominant control mechanism which points to the hip abductors/adductors as the possible dominant muscle group. This hypothesis will be tested in future research during quiet and perturbed balance conditions.

Table 3 summarizes the collaboration between the two mechanisms (COP changes under each foot versus loading/unloading) as seen in the cross correlations between COP_c and COP_v. In several subjects there were high positive correlations in isolated conditions. However, in general the correlations are low and inconsistently positive or negative. This lack of a consistent trend indicates that the minuscule contribution of the smaller component is really not a contribution. Rather, it was acting somewhat randomly, sometimes to assist, sometimes to oppose and sometimes neither.

The two goals of this paper have been demonstrated for both eyes open and eyes closed conditions. In the A/P direction the left and right *COP's* were quite synchronized while in the M/L direction they were antiphase. In the A/P direction the net *COP* changes were virtually 100% controlled by the right and left *COP* changes. However, in the M/L direction the left and right *COP* changes contributed very little to the net *COP* fluctuations. Rather, a dominant loading/unloading response is evident.

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