Postural Control Mechanisms During Quiet Standing in Patients With Diabetic Sensory Neuropathy

Danik Lafond, PhD1,2
Hélène Corriveau, PT, PhD3
François Prince, PhD1,2,4

Objective — The objective of the present study was to compare postural mechanisms identified by using dual force platform in healthy elderly community-dwelling subjects and diabetic sensory neuropathy (DSN) patients under different visual conditions.

Research Design and Methods — The presence and the severity of the sensory neuropathy was evaluated with a clinical scale. Postural mechanisms and motor strategies of the ankle and hip joints were quantified by testing subjects in quiet stance on a dual force platform under two visual conditions (eyes open and eyes closed). Root mean square (RMS) values of the center of pressure (COP) time-varying signals and normalized cross-correlation function were used to estimate the contribution and the interdependence of postural control mechanisms.

Results — DSN patients show larger RMS values of the COPx, displacement in both anteroposterior and mediolateral (ML) directions. Motor strategies at the ankle joints are altered in DSN patients compared with healthy elderly subjects particularly in the ML direction.

Conclusions — This experiment is the first to highlight that even with vision, postural mechanisms at the ankle joints are impaired in DSN patients during quiet standing. Our results point out the importance of focusing on postural control instability in ML of DSN patients.

Diabetes Care 27:173–178, 2004

The postural control system is a complex organization that controls the orientation and the equilibrium of the body during an upright stance (1,2). Past research provides many insights that the postural control system involves sensory afferences integration instead of eliciting reflex responses. Sources of sensory afferences that are viewed to contribute to postural control are 1) vestibular, 2) visual, and 3) proprioceptive. Postural instability in diabetic sensory neuropathy (DSN) patients is usually attributed to the lack of accurate proprioceptive feedback (sensory ataxia) from the lower limbs (3–5). The prevalence of sensory ataxia in diabetic patients ranges from 10 to 90% depending on screening protocol and criteria to define neuropathy (6). Compared with non-neuropathic diabetic patients, DSN patients self-reported 15 times more complaints of instability. The severity of polyneuropathy was quantified using a clinical scale. Postural instability in DSN (3–5,10) but not with diabetes per se (3).

The objective of the present study is to compare postural mechanisms by using dual force platform in healthy elderly subjects and DSN patients. Ankle and hip postural strategies in both AP and ML directions will be investigated and compared.

Research Design and Methods — Eleven elderly patients with type 2 diabetes with DSN and 20 healthy elderly subjects were studied (Table 1). Subjects were age matched because postural instability has been related to age (5,13). The DSN patients were recruited from a diabetes clinic. The DSN patients were not selected based on their complaints of instability. The severity of polyneuropathy was quantified using a scoring system developed by Valk et al. (14). Briefly, a total score of 0 is graded as no polyneuropathy, 1–9 as mild, 10–18 as moderate, and 18–33 as severe polyneuropathy. Valk et al. (15) have shown that this clinical evaluation has a good intrarexaminer reliability and a good sensibility and specificity. Five DSN subjects were classified as mild, four as moderate, and two as having severe polyneuropathy. The eligibility criteria for a healthy subject consisted of being ≥60 years of age, living independently in the community, and having no neurological or musculoskelet
COP analysis and postural control mechanisms definition

When a subject stands erect in double stance on one force platform, the COP is calculated as follows:

\[
\text{COP}_{i}(t) = \frac{-M_{i}(t) + F_{x}(t) \times Z_{0}}{F_{y}(t)} + X_{0} \quad \text{and} \quad \text{COP}_{r}(t) = \frac{M_{r}(t) + F_{x}(t) \times Z_{0}}{F_{y}(t)} + Y_{0}
\] (Eq. 1)

in which \(M\) is the moment, \(F\) is the reaction force, \(x\), \(y\), and \(z\) are, respectively, the ML, AP, and vertical direction, and \(X_{0}\), \(Y_{0}\), and \(Z_{0}\) are the offsets from the geometric center of the force platform.

However, in a double stance on two adjacent force platforms, the COP is determined in AP and ML directions in respect to Eq. 2. The COP is, therefore, the weighted sum of the time-varying position of the COP from each force platform.

\[
\text{COP}_{\text{net}}(t) = \text{COP}_{i}(t) \times \frac{F_{x}(t)}{F_{y}(t)} + \text{COP}_{r}(t) \times \frac{F_{x}(t)}{F_{y}(t)}
\] (Eq. 2)

in which \(\text{COP}_{i}\) and \(\text{COP}_{r}\) are the COP coordinates under the left limb and the right limb, respectively. The following ratio is the time-varying signal representing the relative vertical load (V) under each foot.

\[
\frac{F_{x}(t)}{F_{x}(t) + F_{x}(t)}
\] (Eq. 3)

This ratio is 0.5 when the body weight is equally distributed under each foot.

If the two limbs do not have exactly the same loading on each force plate, Eq. 2 will be modified to reflect the average loading of each limb during the evaluation period.

\[
\text{COP}_{i}(t) = \overline{V}_{i} \times \text{COP}_{i}(t) + \overline{V}_{r} \times \text{COP}_{r}(t)
\] (Eq. 4)

The ratios \(\overline{V}_{i}\) and \(\overline{V}_{r}\) represent the average vertical loads under each foot. Because the \(\overline{V}_{i} = 1 - \overline{V}_{r}\) in quiet standing, the COP is viewed as the motor contribution of ankle plantarflexors/dorsiflexors and ankle evertors/invertors in the AP and ML directions, respectively (12). Now if the COP is removed from the COP, the contribution of the load/unload mechanism, COP, which is reflected by the fluctuations of \(V\), can be estimated as follows:

\[
\text{COP}_{i}(t) = \text{COP}_{\text{net}}(t) - \text{COP}_{i}(t)
\] (Eq. 5)

Biomechanical analysis showed that the COP is attributed to the motor contribution of the hip adductors/abductors (12). Therefore, the COP is the summation of two mechanisms, one relative to the control of ankle musculature (COP) and the other attributed to the control of the hip musculature (COP).

Data collection

Subjects were instructed to stand as still as possible in an upright posture on two adjacent force platforms. Data acquisition was made in a double leg stance with feet at pelvic width. Tracings were done of foot placement, and subjects were required to remain within these tracings for all trials to ensure that feet position remained constant. Under the “eyes open” (EO) condition, subjects were instructed to look straight ahead with their head straight and their arms hanging at their sides in a comfortable position. Four successive trials with eyes open followed by four successive trials with eyes closed (EC) lasting 120 s were collected with a resting period of ~ 5 min between trials. Ground reaction forces and moments were acquired by two AMTI force platforms (Model OR6–5; Advance Mechanical Technology, Waterton, MA). Analog signals were sampled at a frequency of 20 Hz with an A/D converter and recorded on a Pentium computer. Force platforms always allowed the temperature to stabilize for at least 45 min before any data collection to minimize any electronic drifts. The data collected were thereafter transformed (in \(N\) and \(N \times m\)) by multiplying the data array by full calibration matrix to ensure true values of reaction forces and moments. The force platform signals were filtered with a zero lag sixth order Butterworth low pass filter at 10 Hz. The accuracy of the COP measured in the present study is 0.2 mm (10).

Data analysis

A measurement of the average contribution of the COP(t) and the COP(t) to the COP was calculated for each trial from the root mean square (RMS) as follows:

\[
\text{RMS} = \sqrt{\frac{\sum |COP_{i}(t)|^{2}}{N}}
\] (Eq. 6)

in which \(N\) is the number of sample data.

The dependence of between the COP(t) and COP(t) as well as the dependence of the two separates motor mechanisms [COP(t) and the COP(t)] on the
COP_{net}(t) was estimated by a normalized cross-correlation at zero lag to obtain results lying between +1 and −1. The "cross-correlation" measures of the similarity between two different datasets at different time lags. In the present study, we calculated the cross-correlation at zero lag because we are interested in postural mechanisms contributions at the same point in time. If the signals are identical, then the correlation coefficient is 1; if they are totally different, the correlation coefficient is 0; and if they are identical except that trends are moving in the opposite directions (phase is shifted by exactly 180°), then the correlation coefficient is −1. A strong correlation indicates that the information contained in the two COP time series overlap substantially and indicates a dependence of COP time series in this study. All COP time series were calculated and analyzed with MATLAB 5.1 (Mathworks, Natick, MA). The ANOVA and the Student's t test were used to compare healthy subjects with DSN subjects. Statistical significance was assumed at \( P < 0.05 \) (two-tailed).

RESULTS — Comparisons of subject characteristics for the two groups are presented in Table 1. There were significant differences between the two groups in all sensory tests and the Tinetti mobility scale. The COP time-varying signals of one representative trial of 10 s are presented (Fig. 1). Dual force plates first allow quantifying the relative load under each foot. The left and right vertical ground reaction forces are perfectly out of phase as depicted in Fig. 1A. When one limb is unloading, the contralateral limb is loaded proportionally. In AP direction, the COP_{net} trajectory is approximately at the mid-distance between COP_{L} and COP_{R} trajectories (Fig. 1B). However, in the ML direction, the COP_{net} trajectory is not in relation to either COP_{L} or COP_{R} (Fig. 1C). The COP_{net} oscillations are considerably larger than either COP_{L} or COP_{R}. In ML direction, the COP_{L} trajectory is in good agreement to the COP_{net} whereas the contribution of the COP_{R} is negligible (Fig. 1D). In contrast, the COP_{R} trajectory is close to the COP_{net} and the amplitude of the COP_{R} contributing very little to the COP_{net} in the AP direction (Fig. 1E).

The contribution of the COP_{L} and COP_{R} to the COP_{net} displacement was quantified using the RMS values of each of these time-varying signals (Table 2). The RMS of the COP_{net} is significantly greater for the DSN compared with the healthy elderly subjects in both AP and ML directions. The mean RMS values during EO conditions were 1.97 and 3.58 mm for the
healthy group, whereas the DSN groups present a higher value with a mean of 2.77 and 4.91 mm in ML and AP, respectively. For the healthy group, the EC condition significantly increases the COPc, COPv, and COPnet in AP direction. In ML, the RMS values of the COPc and the COPnet were increased significantly (P < 0.05) during the EC compared with the EO conditions but not the COPv. It should be noted, however, that the COPc in ML and the COPv in AP have limited contribution to the COPnet. DSN patients show a significant increase of RMS values of the COPc and COPnet during EC condition in the AP direction only. When expressed in percentage of COPnet (%COPnet), there is no difference between healthy subjects and DSN patients for the COPc and COPv in both AP and ML directions. There is an effect of vision where the EC condition reduces the relative contribution of the COPc in ML and the COPv in AP for the healthy group.

The dependence or the independence between COP time-varying signals was quantified by the normalized cross-correlation function (Table 3). In general, there is a very strong and significant correlation between COPc and COPnet and between COPv and COPnet in AP and ML, respectively. A relatively high and significant correlation between COPc and COPv (mean ± SD, 0.64 ± 0.19) and between COPnet and COPnet (0.77 ± 0.14) is found for the healthy group in ML. This high dependence is significantly decreased in DSN patients compared with healthy elderly individuals (0.81 ± 0.06). The relation between COPc and COPnet is high for the healthy subjects (0.60 ± 0.52) and DSN patients (0.54 ± 0.63) during EC condition. This relation is significantly increased in DSN patients (0.81 ± 0.06) compared with healthy elderly individuals (0.62 ± 0.56) during EC. For the healthy group, the EC condition decreases significantly the dependence between COPc and COPv and between COPc and COPnet in the ML direction. However, in the AP direction, only the relation between COPc and COPv is affected by the vision conditions. In DSN patients, the dependence between COPc and COPv was affected by vision in the ML direction. In AP, the dependence between COPc and COPv is significantly increased, and the relation between the COPc and COPnet is affected significantly in AP.

**CONCLUSIONS** — Several studies have demonstrated, using summary COP measures, that DSN patients have a poor postural control during quiet standing compared with healthy elderly individuals. DSN showed larger sway area (3.17, 18), larger speed of sway (3.17, 18), larger COP range (3.5), higher RMS values of the COP-COM variable (10), and an increase in the power of medium-high frequency band (4.17) of a power spectral analysis. Our results confirm the findings of previous research regarding postural instability of DSN patients in quiet standing. The present study showed RMS values of COPnet in DSN patient during EO that are comparable with the EC results of age-matched healthy elderly subjects as found previously (3). These results highlighted that DSN patients, not selected for any complaint of instability a priori, have

---

### Table 2—RMS of the COPc, COPv, and COPnet

<table>
<thead>
<tr>
<th></th>
<th>ML Eyes open COPc</th>
<th>ML Eyes closed COPc</th>
<th>ML Eyes open COPv</th>
<th>ML Eyes closed COPv</th>
<th>ML Eyes open COPnet</th>
<th>ML Eyes closed COPnet</th>
<th>AP Eyes open COPc</th>
<th>AP Eyes closed COPc</th>
<th>AP Eyes open COPv</th>
<th>AP Eyes closed COPv</th>
<th>AP Eyes open COPnet</th>
<th>AP Eyes closed COPnet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Healthy elderly subjects</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>0.31 ± 0.10</td>
<td>1.84 ± 0.54*</td>
<td>1.97 ± 0.53*</td>
<td>0.32 ± 0.08</td>
<td>2.27 ± 0.86*</td>
<td>2.39 ± 0.81*</td>
<td>3.70 ± 1.14*</td>
<td>0.26 ± 0.21*</td>
<td>3.58 ± 1.02*</td>
<td>4.07 ± 1.13*</td>
<td>0.29 ± 0.22*</td>
<td>3.92 ± 1.02*</td>
</tr>
<tr>
<td>%COPnet</td>
<td>16.8</td>
<td>92.9</td>
<td>—</td>
<td>14.6</td>
<td>94.1</td>
<td>—</td>
<td>103.0</td>
<td>13.9</td>
<td>103.2</td>
<td>7.1</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Patients with diabetic sensory neuropathy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>0.56 ± 0.18</td>
<td>2.63 ± 0.98</td>
<td>2.77 ± 0.97†</td>
<td>0.59 ± 0.18</td>
<td>4.06 ± 3.61</td>
<td>4.13 ± 3.69†</td>
<td>5.01 ± 1.57</td>
<td>0.27 ± 0.10*</td>
<td>4.91 ± 1.56†</td>
<td>5.49 ± 1.56</td>
<td>0.43 ± 0.20*</td>
<td>5.53 ± 1.56†</td>
</tr>
<tr>
<td>%COPnet</td>
<td>22.1</td>
<td>94.7</td>
<td>—</td>
<td>17.8</td>
<td>98.6</td>
<td>—</td>
<td>102.3</td>
<td>11.2</td>
<td>—</td>
<td>99.3</td>
<td>8.2</td>
<td>—</td>
</tr>
</tbody>
</table>

Values are in millimeters. *Significant difference (P < 0.05) between EO and EC conditions. †Significant difference (P < 0.05) between healthy elderly subjects and DSN patients.
a poor postural control that may lead them to a higher risk of falling.

The COPnet is equivalent of the COP measured from one force platform. However, the contributions of the individual limbs were not possible until two platforms were used to identify independent postural mechanisms. The COPp and the COPr represent the postural control at the ankle and hip, respectively. Therefore, the main objective of this study was to compare DSN patients with healthy elderly subjects using postural control mechanisms developed and measured with dual force platforms. The ankle and hip postural mechanisms that have different contributions in AP and ML directions have been calculated. In ML, the COPc has only a negligible effect as shown by low RMS values in the two groups. However, the COPp contributes almost totally to the COPnet in AP. This dominance in AP has been attributed by biomechanical inverse dynamics to the activation of the ankle plantar flexors/dorsiflexors motor control (12). It is not surprising if one considers the axes of rotation of the ankle joints and their symmetrical alignment during quiet standing. Furthermore, the COPp and COP trajectories vary synergistically in AP. This observation is supported by high cross-correlation coefficients between COPp and COP in both healthy subjects and DSN patients. In addition, the COPnet is perfectly in phase and dependant of the COPp in AP. In contrast, the COPp in ML contributes to over 90% of the COPnet, whereas in AP, its contribution is only ~15–20%. This loading/unloading mechanism dominant in ML has been attributed to the control of the hip adductors/abductors (12). Evidence of hip adductors/abductors motor control in quiet standing in ML direction is supported by the dependence of the COPc and COP trajectories and by the almost perfect correlation between COPp and COPnet. A closer look on the relation between COPc and COPp in healthy elderly subjects reported out of phase changes with an average cross-correlation coefficient of −0.55. This result is in agreement with those reported in young healthy adults of approximately −0.68 (12). This means that the COPp tends to cancel out the COPc when the COP trajectory changes medially by right ankle eversion motor activity, there is a similar left ankle eversion motor activity tending to change medially the COPp trajectory. However, in DSN patients, this relation is decreased, and low cross-correlation coefficients have been attempted with higher variability. In ML, the relation between COP and COPp is positively correlated with very low variability in healthy elderly subjects. DSN patients have obtained a significantly lower correlation between COP and COPp lying around zero with a relatively high standard deviation. Furthermore, the relation between COPc and COPnet is significantly lower in DSN patient compared with healthy elderly individuals. Our results showed that left and right eversion/inversion motor activities are not as well matched in DSN patients as seen in age-matched healthy subjects. This study is the first to demonstrate that ankle motor activities are affected in DSN patients during quiet standing.

The effect of vision was significant in the RMS values of all COP time-varying signals in both AP and ML directions for the healthy group. However, only RMS values of COPp and COPnet in AP were affected by vision deprivation in the DSN group. The dependence or independence of the COP time-varying signals were not differently affected by vision compared with healthy elderly subjects in ML. These results supported the findings previously discussed that postural control mechanisms are affected in ML even with vision in DSN subjects. Our results point out the importance of focusing on postural control instability in ML of DSN patients.

Table 3—Normalized cross-correlation values in the AP and ML directions for all COP time-varying signals

<table>
<thead>
<tr>
<th>Healthy elderly subjects</th>
<th>DSN patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eyes open</td>
<td>Eyes closed</td>
</tr>
<tr>
<td>COPp versus COPp</td>
<td>−0.55 ± 0.32</td>
</tr>
<tr>
<td>COPr versus COPp</td>
<td>0.64 ± 0.19*</td>
</tr>
<tr>
<td>COPp versus COPnet</td>
<td>0.77 ± 0.14</td>
</tr>
<tr>
<td>COPr versus COPnet</td>
<td>0.99 ± 0.01</td>
</tr>
<tr>
<td>AP direction</td>
<td></td>
</tr>
<tr>
<td>COPp versus COPp</td>
<td>0.77 ± 0.13*</td>
</tr>
<tr>
<td>COPr versus COPp</td>
<td>−0.63 ± 0.51</td>
</tr>
<tr>
<td>COPp versus COPnet</td>
<td>1.00 ± 0.00</td>
</tr>
<tr>
<td>COPr versus COPnet</td>
<td>−0.60 ± 0.52</td>
</tr>
</tbody>
</table>

Data are means ± SD. *Significant difference (P < 0.05) between EO and EC conditions. †Significant difference (P < 0.05) between healthy elderly subjects and DSN patients.

References


