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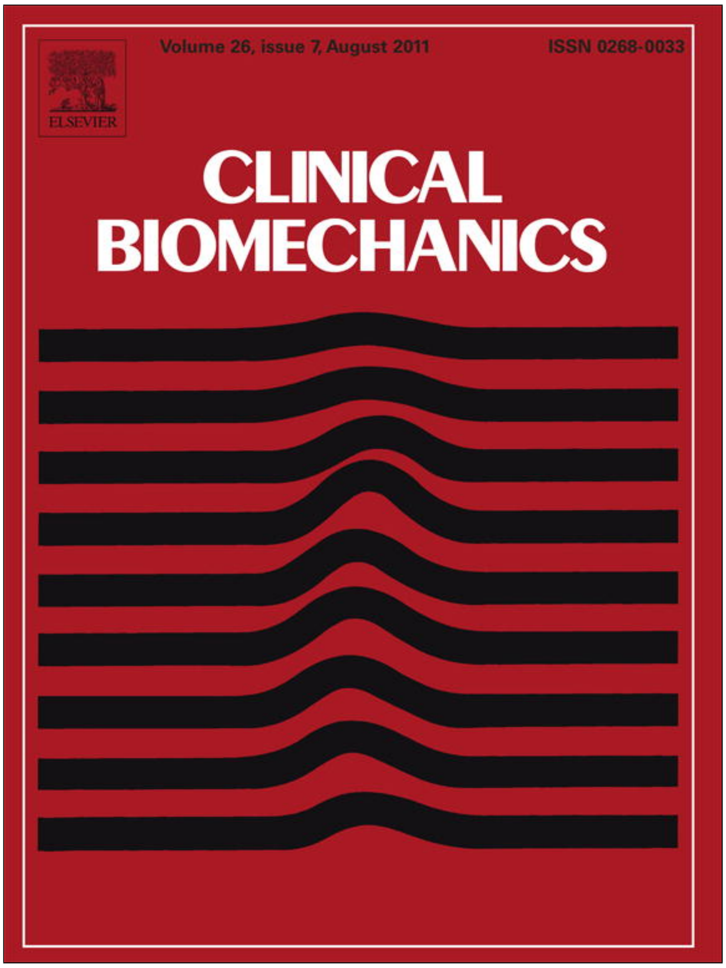

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Review

Peripheral neuropathy may not be the only fundamental reason explaining increased sway in diabetic individuals

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ABSTRACT

Background: Individuals with diabetic neuropathy sway more than control individuals while standing. This review specifically evaluated whether peripheral sensory neuropathy can be the only fundamental reason accounting for significant increased sway within this population.

Methods: Twenty-six experimental articles were selected using MEDLINE and reference lists of relevant articles. The articles chosen investigated kinematic data of postural behaviour in controls and individuals with diabetic neuropathy during stance. Results of literature were compared with four expectations related to the peripheral sensory neuropathy fundamental hypothesis.

Findings: Consistent with the peripheral sensory neuropathy hypothesis, the literature showed that individuals with diabetic neuropathy sway more than controls in quiet stance and even more so if their visual or vestibular systems were perturbed. Inconsistent with the hypothesis, individuals with diabetic neuropathy are more destabilised than controls in conditions altering sensation of the feet and legs (standing on a sway-referenced surface).

Interpretation: The review showed that the peripheral sensory neuropathy hypothesis may not be the only fundamental cause accounting for significant increased postural sway in individuals with diabetic neuropathy. Visual impairments and changes in postural coordination may explain the divergence between expectations and results. In order to develop interventions aimed at improving postural control in individuals with diabetic neuropathy, scientific exploration of these new expectations should be detailed. Also at the practical level, the review discussed which additional sensory information – at the level of the hands and feet – may be more beneficial in individuals with diabetic neuropathy to reduce their postural sway.

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1. Introduction

Diabetes is a metabolic disease that affects up to 285 million people (aged 20–79 years) worldwide in 2010 (Shaw et al., 2010). This disease is a veritable economic burden for Health Care System and for individuals (Engelgau et al., 2004) because of disease-related symptoms (e.g., asthenia, thirst and polyuria) and complications from mismanagement (e.g., amputation, blindness). A complication such as neuropathy impairs action and perception capabilities of a person, thus causing other issues such as postural instability and falls. Diabetic individuals over 65 years old are almost three times more likely than matched controls (C) to be hospitalised in a given year (Zaida and Alexander, 2001) due to fall related injuries. Postural instability is a strong predictor of falls (Lord et al., 1994). For this reason, this review analyses postural instability in individuals with diabetic neuropathy (DN).

In the literature, individuals with DN have been shown to exhibit stance instability (Nardone et al., 2006; Yamamoto et al., 2001). Individuals with DN even are unstable in the early stages of their neuropathy (e.g., Corriveau et al., 2000), but not before neuropathy affects their body (Bonnet et al., 2009). It is well known that neuropathy is more peripheral than central (Cavanagh et al., 1993; Uccioli et al., 1997). Neuropathy is also mainly sensorial before being motor and autonomic (Cavanagh et al., 1993; Uccioli et al., 1995). Since somatosensory information has an important role in postural control (Simoneau et al., 1995), the *peripheral sensory neuropathy hypothesis* has been proposed as a fundamental cause explaining postural instability in individuals with DN. According to this hypothesis, individuals with DN

Abbreviations: DN, diabetic neuropathy; C, control individuals; D, with diabetes but without neuropathy; EO, eyes open; EC, eyes closed; AP, antero-posterior; ML, medio-lateral; CoP, center of pressure; CoM, center of mass.

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Table 1
Summary of twenty-six articles comparing center of pressure/body sway in individuals with diabetic neuropathy and in healthy control individuals.

References	No. of participants		Experimental conditions	Kinds of perturbation/facilitation	Device(s) to measure COP/body sway	Dependent variables used
	DN	HC				
Bergin et al. (1995)	25	32	Combination of: • EO and EC • Firm and foam surface	• None • Only visual • Only somatosensory • Visual + somatosensory	Force platform	(CoP of) AP path length, Romberg Quotient of AP path
Boucher et al. (1995)	12	7	EO, EC, EC halfway and EO halfway	• None • Only visual	Force platform	(CoP of) scalar range, mean velocity, sway dispersion (no detail for direction), AP and ML range
Cavanagh et al. (1993)	16	16	EO	none	Force platform	(CoP of) total path length, AP and ML range (absolute or expressed as a percentage of stability margin), mean power frequency (no detail for direction), AP stability margin (absolute and relative to the foot),
Corriveau et al. (2000)	15	15	EO and EC	• None • Only visual	Force platform; 21 markers attached on the body (to calculate the position of the CoM)	Root mean square of CoP–CoM, Romberg Quotient of root mean square of CoP–CoM (both in the AP and ML axes)
Dickstein et al. (2003)	8	10	Combination with EC: • 3 touch conditions (no touch, light touch, heavy touch)	• Visual + somatosensory • Visual + somatosensory but with facilitation (fingertip touch)	Force platform	(CoP of) response latency, AP scaling of initial postural response to platform velocity (velocity of the platform/initial rate of change), AP and ML initial velocity
Dickstein et al. (2001)	8	8	Combination: • 3 touch conditions (no touch, light touch, heavy touch) • 2 eyes condition (EO, EC) • 2 support surfaces (firm or foam)	• None • Only visual • Only somatosensory • With facilitation (fingertip touch) • Visual but with facilitation (fingertip touch) • Visual + somatosensory • Somatosensory but with facilitation (fingertip touch) • Visual + somatosensory but with facilitation (fingertip touch)	Force platform; Marker at the trunk (Watson angular rate sensor, which was attached to the sternum)	Root mean square of CoP displacement, root mean square of trunk velocity (both in the AP and ML axes)
Di Nardo et al. (1999)	14	24	6 conditions for the Sensory Organization Test: EO, EC, EO and moving surround, EO and moving platform, EC and moving platform, EO and moving platform and surround	• None • Only visual • Only somatosensory • Visual + somatosensory	Force platform	(Obtained from the CoP) equilibrium score = percentage of fluctuation related to the maximum possible inclination (12.5°) in the AP axis

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Giacomini et al. (1996)	10	21	EO and EC	• None • Only visual	Force platform	(CoP of) mean velocity, SD of velocity, VFY (no detail for direction), AP and ML FFT
Hijmans et al. (2008)	17	15	Vibrating insoles turned on halfway, first half or second half: • 1st trial: EO looking straight ahead. • 2nd trial, 3 rd trial, and 4th trial (in random order): EC; EO and performing an attention- demanding task (subtracting 6 from a random number; EC and performing an attention- demanding task) • 5th trial: EO looking straight ahead	• None • Only visual • Increased difficulty (cognitive task) • Visual + increased difficulty (cognitive task) • With facilitation (body touch) • Visual but with facilitation (body touch) • Increased difficulty (cognitive task) but with facilitation (body touch) • Visual + increased difficulty (cognitive task) but with facilitation (body touch)	Force platform	Mean velocity (in mm/s), root mean square of the velocity in the AP and the ML axes
Horak et al. (2002)	13	12	EO and EC, Combination of: • EO and EC • CoP, CoM and ankle angle sway referenced conditions	• None • Only visual • Only somatosensory • Visual + somatosensory	Force platform; Potentiometers at the shoulder and at the hip (to calculate the position of the CoM using a two segments mode)	CoM and CoP velocity variance, AP range of CoM and CoP
Horak and Hlavacka (2001)	8	8	Combination with EC and head turn right or left: • No stimulation or galvanic stimulation at 0.25 mA, 0.5 mA, 0.75 mA, or 1 mA • Stance on three different surfaces (rigid, 5 cm of compliant foam, and 10 cm compliant foam)	• Visual + vestibular • Visual + vestibular + somatosensory	Force platform; 32 markers attached on the body (to calculate the position of the CoM)	Average amplitude of the displacement of CoP, CoM, and trunk segment orientation, slope of the linear regressions between the CoP, CoM, or trunk final position response as a function of stimulus intensity, CoM angle and trunk angle (all these variables in the AP axis)
Katoulis et al. (1997)	40	20	EO and EC	• None • Only visual	Force platform	(CoP of) Romberg Quotient of SD, SD (both in the AP and ML axes)
Lafond et al. (2004)	11	20	EO and EC	• None • Only visual	Force platform	CoPleft, CoPright, CoPc, CoPl, CoPnet (in the AP and ML axes)
Nardone et al. (2007)	14	21	Combination of: • EO and EC • Stationary platform or platform producing a horizontal sinusoidal (0.2 Hz) movement (peak to peak 6 cm)	• None • Only visual • Only somatosensory • Visual + somatosensory	Force platform; Reflexive markers at the ankle at the trunk and at the head	(CoP of) mean position, area, head SD, path length of head and malleolus displacement, correlation coefficient between head and feet, time lag between the head and malleolus displacement (all variables in the AP axis)
Nardone et al. (2006)	14	20	Combination of: • EO and EC • Stationary platform or platform producing a horizontal sinusoidal (0.2 Hz) movement (peak to peak 6 cm)	• None • Only visual • Only somatosensory • Visual + somatosensory	Force platform; Reflexive markers at the ankle and at the head	(CoP of) mean position, area, SD of head and hip displacement, correlation coefficient between head and feet, time lag between the head and malleolus displacement, head to hip ratio (all variables in the AP axis)
Nardone and Schieppati (2004)	22	13	Combination of: • EO and EC • Feet 10 cm apart or feet together	• None • Only visual • Increased difficulty (feet together)	Force platform	(CoP of) area, AP and ML normalized average position of CoP

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Table 1 (*continued*)

References	No. of participants		Experimental conditions	Kinds of perturbation/facilitation	Device(s) to measure COP/body sway	Dependent variables used
	DN	HC				
Oppenheim et al. (1999)	20	30	Combination of: • EO and EC • Firm and foam surface + conditions with head straight, turned right, left, up, or down with EC	• None • Only visual • Only somatosensory • Visual + somatosensory • Vestibular + visual	Force platform	(CoP of) path length, Fourier analysis in 4 independent wave signals: 0.01–0.1 Hz; 0.1–0.5 Hz; 0.5–1 Hz; and 1–3 Hz (no detail for direction of analyses)
Priplata et al. (2006)	15	12	EC, EC with mechanical noise	• Only visual • Visual but with feet facilitation (vibration)	Reflexive marker at the shoulder	Traditional variables: mean stabilogram radius, area swept by the stabilogram over time, maximum radius of sway, AP and ML range of displacement Non-linear variables (from the detrended fluctuation analysis): critical mean square displacement, long-term diffusion coefficient, long-term scaling exponent (all these variables normalized with respect to the height of the participant)
Schilling et al. (2009)	28	39	3 trials with EC	Only visual	Force platform	Composite feature, quiet standing index
Simmons et al. (1997)	23	50	6 conditions for the Sensory Organization Test: EO, EC, EO and moving surround, EO and moving platform, EC and moving platform, EO and moving platform and surround	• None • Only visual • Only somatosensory • Visual + somatosenosrial	Force platform	(Obtained from the CoP) equilibrium score, hip-ankle strategy score, composite score (all variables in the AP axis)
Simoneau et al. (1994)	17	17	Combination of: • EO and EC • Head straight and head back (45°)	• None • Only visual • Only vestibular • Visual + vestibular	Force platform	CoP total path length
Simoneau et al. (1995)	17	17	Combination of: • EO and EC • Head straight and head back (45°)	• None • Only visual • Only vestibular • Visual + vestibular	Force platform	(CoP of) total path length, area, AP and ML range
Turcot et al. (2009)	12	12	EO and EC	• None • Only visual	Accelerometers at lumbar and at ankle levels	Range and root mean square (both in the AP and ML axes)
Uccioli et al. (1995)	10	21	EO and EC	• None • Only visual	Force platform	(CoP of) total path length, area, mean velocity, Romberg Quotient of area
Uccioli et al. (1997)	7	31	EO and EC	• None • Only visual	Force platform	(CoP of) total path length, area, mean velocity, SD of velocity, VFY
Yamamoto et al. (2001)	32	55	EO and EC	• None • Only visual	Force platform	(CoP of) total path length, area, path length/area, Romberg Quotient (no precision for the variable used), AP and ML SD

Reference of the twenty-six reviewed articles with details about the participants, the experimental conditions, the kind of perturbation/facilitation, the device(s) used to record center of pressure/body sway, and the dependent variables analyzed. This table only reports relevant information relative to the two groups of interest (individuals with diabetic neuropathy and healthy controls).

Therefore, results and information of other participants are not reported. Only experimental conditions and dependent variables that could be used to test the peripheral sensory neuropathy hypothesis are reported. Abbreviations: No. = number; DN = individuals with diabetic neuropathy; C = healthy control individuals; EO = eyes open; EC = eyes closed; CoM = center of mass; CoP = center of pressure; AP = antero-posterior axis; ML = medio-lateral axis; VFY = standard deviation of the velocity of the CoP as a function of the AP position of the CoP; SD = standard deviation. FFT=Fast Fourier Transform; COPc and COPv=COPchanges and COPvertical respectively; COPleft and COPright=COP under the left and right foot respectively; COPnet=integrated displacements of the COP under each foot.

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are unstable because they experience diminished somatosensory information at the level of the feet, ankles, and legs. In this review, *fundamental* and *secondary* factors are causes that can significantly increase postural sway by themselves alone or only in combination to other factors, respectively. Consistent with the peripheral sensory neuropathy hypothesis, literature systematically revealed significant relationships between peripheral sensory neuropathy (at both sensory discrimination and neural responsiveness levels) and postural instability (Bonnet et al., 2009). Consistent with former authors, we believed that peripheral sensory neuropathy is the primary cause of postural instability in individuals with DN. The goal of this review was to test the classical hypothesis that peripheral sensory neuropathy is the only fundamental cause explaining postural instability in individuals with DN (e.g., Bergin et al., 1995; Corriveau et al., 2000; Horak et al., 2002). Before the development of interventions aimed at restoring DN's postural stability, the list of fundamental causes of their instability must be detailed.

2. Methods

2.1. Articles selected

The articles selected for the review compared center of pressure sway (from force platform) and/or body sway (recorded with markers placed on the body) of C and DN individuals standing upright. Results of other participants than C and DN individuals were not discussed even in the articles selected for the review. Studies that explored the association between diabetic neuropathy and postural stability in MEDLINE were analysed. Search terms included both general and common derivations related to postural control (postural control, postural sway, postural stability, stance, and balance) and the disease (diabetes, diabetic neuropathy). Twenty-five articles were found. Additionally, the reference lists of these articles were investigated and four articles were added to the list (Bergin et al., 1995; Cavanagh et al., 1993; Mimori et al., 1982; Simoneau et al., 1995). Three articles were rejected because inclusion/exclusion criteria were either excluded or minimally mentioned (Ahmmed and Mackenzie, 2003; Mimori et al., 1982; Rogers et al., 2001). These articles were rejected because uncontrolled secondary factors can combine their effects and may cause a difference in postural sway between individuals with DN and C. The list of the 26 reviewed articles is shown in Table 1. Additionally, different combinations of secondary factors can lead to different effects on postural sway.

In the following sections, expectations consistent with the peripheral sensory neuropathy hypothesis are proposed. Then, the concordance of published results with these expectations are verified.

2.2. Expectations

In stance, healthy individuals sway continually (Hinsdale, 1887) even if postural control relies on three kinds of information (visual, vestibular, and somatosensory). Postural control thus can be said to be *imperfect*, if the term *imperfect* is used in the sense that the body sways less if it can pick up additional useful information for postural control (e.g., touch of a surface with finger tips; Jeka and Lackner, 1995).

As postural control is imperfect, the lesser the perceptual information available, the more postural sway increases (Simoneau et al., 1995). In static conditions with no stimulation of any kind, somatosensory information contributes to 60–75% of postural control (Simoneau et al., 1995). Therefore, according to the peripheral sensory neuropathy hypothesis, individuals with DN are expected to be unstable in quiet stance with eyes open (1st expectation; e.g., Cavanagh et al., 1993). Furthermore, disrupting several perceptual systems were expected to increase postural sway more than disrupting each perceptual system separately (Simoneau et al., 1995; cf. Table 2). Thus, visual or vestibular perturbations were expected to increase center of pressure (CoP)/body sway more in individuals with DN than in C, due to already having somatosensory loss at their feet and legs (2nd expectation). The most important difference in CoP/body sway between both groups were expected in conditions including both visual and vestibular perturbations on a rigid surface (3rd expectation).

When standing on a sway-referenced platform, individuals are deprived of somatosensory information at the feet (Horak et al., 2002). Thus, consistent with the peripheral sensory neuropathy hypothesis, individuals with DN were not expected to sway more than C in such sway-referenced conditions, even if the visual and/or the vestibular system are also perturbed (4th expectation). In other conditions (e.g., on foam), the 4th hypothesis were not be tested because no author confirmed that the somatosensory information at the feet is fully disrupted.

2.3. Selection of the patients with DN in each study

Many methods exist to diagnose and to quantify peripheral neuropathy (Greene et al., 1990). However, only one clinical method such as the Vibration Perception Threshold test has been documented to provide reliable findings (Jia et al., 2006). In the twenty-six articles, analysed for this review: the Vibration Perception Threshold test (Cavanagh et al., 1993; Hijmans et al., 2008; Priplata et al., 2006; Simoneau et al., 1994, 1995; Simmons et al., 1997; Turcot et al., 2009); a combination of clinical tests (Boucher et al., 1995; Corriveau et al., 2000; Katoulis et al., 1997; Lafond et al., 2004; Nardone and Schieppati, 2004; Oppenheim et al., 1999); several electrophysiological measures of peripheral nerves (Bergin et al., 1995; Dickstein et al., 2001, 2003; Schilling et al., 2009; Yamamoto et al. 2001); or a combined method with electrophysiological and clinical tests (Di Nardo et al., 1999; Giacomini et al., 1996; Horak et al., 2002; Horak and Hlavacka, 2001; Nardone et al., 2006, 2007; Uccioli et al., 1995, 1997) were used to diagnose and to quantify peripheral neuropathy.

In the reviewed studies, participants were 50 years old or older except in Di Nardo et al. (1999), Giacomini et al. (1996), Oppenheim et al. (1999), Uccioli et al. (1995, 1997), in which participants were 30 to 50 years old. Some studies only investigated type I or type II diabetic individuals (Corriveau et al., 2000; Di Nardo et al., 1999; Horak and Hlavacka, 2001; Lafond et al., 2004; Uccioli et al., 1995,

Table 2

Increased in center of pressure excursion when the participants' perceptual systems are perturbed.

Table adapted from Fig. 2 of "Role of somatosensory input in the control of human posture" by Simoneau, G.G., Ulbrecht, J.S., Derr, J.A., Cavanagh, P.R., Gait Posture 1995, 3, 115–122. Copyright 1995 by Elsevier Science. Adapted with permission. Increased in center of pressure (CoP) path length in conditions perturbing one sensory system (vestibular, visual, somatosensorial) or a combination of these sensory systems. Center of pressure sway in these conditions were compared to the control condition in which healthy individuals stood with eyes open (EO) with no perturbation. The vestibular perturbation was done by asking healthy control participants to keep their head turned. The visual perturbation was done by asking healthy control participants to keep their eyes closed. The somatosensory perturbation was done by recording CoP sway of individuals with diabetic neuropathy. For details, see Simoneau et al. (1995).

	One system perturbed			Two systems perturbed			Three systems perturbed
	Vestibular	Visual	Somato-sensory	Vestibular + visual	Vestibular + somatosensory	Visual + somatosensory	Vestibular + visual + somatosensoryy
Increased in CoP path length compared to baseline (EO, no perturbation)	+4%	+41%	+66%	+ 61%	+72%	+150%	+250%

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1997; Yamamoto et al., 2001); otherwise the type of diabetes was mixed or not delineated. The main exclusion criteria was: recent surgery or injury, vestibular problem, dependence, problem at the feet, bad health conditions (e.g., problem at the heart), neurological disease or medication intake that impacts postural control.

2.4. Conditions and measures

In the reviewed studies (Table 1), researchers often asked their participants to stand still or to stand relaxed with their arms along their side. Trials lasted from twenty seconds to two minutes. Participants were asked either to keep their eyes open or to keep their eyes closed during trials. Environmental conditions were varied (e.g., standing on a firm vs. a foam surface). Devices and dependent variables used are described in Table 1. Analyses described below only compared CoP sway or body sway of individuals with DN and C.

3. Results section

3.1. Conditions with eyes open on a firm surface

Eighteen authors compared CoP/body sway of C and DN individuals who kept their eyes open (EO) in quite stance (Table 1). Table 1 shows 22 studies with no perturbation in the 4th column (mark “none”) because four authors did not reveal the results of the between-groups comparison of COP/body sway in the EO condition (Boucher et al., 1995; Dickstein et al., 2001; Hijmans et al., 2008; Yamamoto et al., 2001). In each of the eighteen articles, at least one analysis revealed that CoP/body sway was greater in individuals with DN than in C. Results in literature were thus deeply consistent with the 1st expectation. As a result, finding that individuals with DN sway significantly more than C in more difficult conditions was a "standard" that could not bring any new knowledge by itself. For this reason, the discussion of assumptions 2, 3, 4 and 5 bears on significant group by condition interaction effects in ANOVAs and on main effects of combined variables (for example, the Romberg Quotient = variable obtained with EC/same variable obtained with EO).

3.2. Conditions with visual or vestibular perturbations on a firm surface

Twenty-three authors compared CoP/body sway of C and DN individuals tested in conditions perturbing the visual information (Table 1, see the mark "only visual" in the 4th column). The authors either asked their participants to keep their eyes closed (EC), to open their eyes halfway through the trial (Boucher et al., 1995) or to look at a moving background (Di Nardo et al., 1999; Simmons et al., 1997). Four authors perturbed the vestibular information of their participants in their experiment (Table 1). They did so either by asking participants to keep their head turned to the right, left, up, down (Simoneau et al., 1994, 1995, Oppenheim et al., 1999) or by applying galvanic stimulations (Horak and Hlavacka, 2001).

3.2.1. Results with only a visual perturbation

The five authors (Boucher et al., 1995; Horak et al., 2002; Nardone et al., 2006, 2007; Nardone and Schieppati, 2004) who realised varying visual conditions and ANOVAs did not report any significant group by condition interaction effect showing significant differences in CoP/body sway between DN and C individuals. Five authors compared the Romberg Quotient of C and DN individuals (Table 1, see 6th column). Only in Bergin et al. (1995), the Romberg Quotient on CoP antero-posterior (AP) path length was significantly higher in individuals with DN (mean 2.7, SD 1.0) than in C (mean 1.9, SD 0.6). In Boucher et al. (1995), the participants realised an EO condition, an EC condition, and a condition in which they opened their eyes after half of the trial (Table 1). Individuals with DN – but not C – showed significantly greater CoP sway for the second half of the trial when they opened their eyes half way compared to when they kept them open. This was the case in the medio-lateral (ML) for range, scalar range and mean velocity of center of pressure sway. These results were consistent with the 2nd expectation.

3.2.2. Results with only a vestibular perturbation

There is no ANOVA in literature.

3.2.3. Results with both visual and vestibular perturbations

In some conditions, Horak and Hlavacka (2001) asked their participants to keep their EC with their head turned left or right when galvanic stimulations were used (Table 1). Consistent with the 3rd expectation, the increase in range of CoP sway was significantly more pronounced for individuals with DN than for C as a response to galvanic stimulation (0.75 and 1 mA). However in the same difficult condition, individuals with DN did not exhibit greater CoP sway than C when there were no or low galvanic stimulation (0.25 and 0.5 mA). Results in literature were thus ambiguous with respect to the 3rd expectation.

3.3. Conditions with somatosensory perturbations

Only three authors compared CoP/body sway of C and DN individuals tested in conditions using sway-referenced moving platforms (Di Nardo et al., 1999; Horak et al., 2002; Simmons et al., 1997). In these conditions, whatever the visual and vestibular perturbation, no group by condition interaction effect and no main effect of group were expected in statistical analyses (4th expectation).

In conditions with only somatosensory perturbation, either CoP/body sway of C and DN individuals were similar (Di Nardo et al., 1999) or significantly greater in individuals with DN (Simmons et al., 1997). In conditions with both somatosensory and visual perturbations, simple comparisons of sway (e.g., *t*-test) showed that CoP/body sway were significantly greater in individuals with DN than in C (Di Nardo et al., 1999; Simmons et al., 1997). With more complex comparisons of sway (ANOVAs with multiple factors), Horak et al. (2002) did not notice any significant difference in sway between C and DN individuals (see Table 1 for the dependent variables and conditions). Overall, the results were inconsistent with hypothesis 4 because individuals with DN were more destabilised than expected.

3.4. Complementary review: conditions with a facilitator

In the reviewed literature, four authors compared CoP/body sway of individuals with DN and C in conditions using a *facilitator* (Dickstein et al., 2001, 2003; Hijmans et al., 2008; Priplata et al., 2006). By facilitator, it is meant useful supplementary information for postural control. In healthy individuals for example, facilitators include the use of canes (Jeka and Lackner, 1995) and infraliminary stimulations under the feet (Priplata et al., 2003).

As stated earlier, individuals with DN sway significantly more than C, which should mean that they need to stabilize their posture more than C. In theory, if individuals with DN could pick-up a facilitator, they may reduce their body sway more than C. Also, the harder the experimental condition, the more individuals with DN could be expected to benefit from a facilitator, and also more than C. However, such expectations cannot be tested with already published articles (Dickstein et al., 2001, 2003; Hijmans et al., 2008; Priplata et al., 2006). Indeed, since peripheral neuropathy affects both hands and feet (Greene et al., 1990), one could not be sure whether individuals with DN should benefit more, less or identically than C the help of such hands (Dickstein et al., 2001, 2003) or feet (Hijmans et al., 2008; Priplata et al., 2006) facilitators. Below, we only reviewed these four articles to discuss important contrasting results between individuals with DN and C.

Dickstein et al. (2001) wanted to know if individuals with DN can improve their CoP and body stability with fingertip touching on a stable surface (with their index finger). The authors compared DN and

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C participants in twelve conditions combining the eyes status (EO or EC), the support surfaces (firm or foam), and the touch mode (no touch; light touch of the surface with less than 1 N of pressure; heavy touch = as much pressure as the participants want). The MANOVAs with the four factors did not reveal that individuals with DN better improved their COP/body stability than C with the facilitator. Additionally, although touch was possible post-hoc analyses showed that standing on foam increased the DN individuals' trunk root mean square velocity axis significantly more than C's one in the ML.

Dickstein et al. (2003) tested conditions combining three touch modes (no touch, light touch, and heavy touch) and three backward translation velocities of the platform (10 cm/s, 20 cm/s, and 30 cm/s; Table 1). DN and C participants kept their EC during the different conditions. As in 2001, Dickstein et al. (2003) did not reveal any significant group by condition interaction effect in their three-way ANOVAs. Individuals with DN did not take advantage from light touch (no change compared to the no touch condition; post-hoc analyses) – while C did; the variable analyzed was the initial AP CoP velocity to platform velocity.

Priplata et al. (2006) wanted to know if DN and C participants could improve their body stability (registered at the level of the shoulder) with sub-sensory mechanical noise applied to the soles of the feet. The participants stood quietly with EC in two conditions, either with or without such sub-sensory noise stimulation (Table 1). A significant group by stimulation interaction effect was found in their regression with a variable combining all seven dependent variables together (see Table 1 for the list of variables). Their results revealed that individuals with DN improved their stability better than C thanks to the facilitator.

Hijmans et al. (2008) conducted a similar experiment that Priplata et al. (2006) with four combined factors: group, vision (EO vs. EC), task performed (nothing vs. subtracting six from a random number), and vibration under the feet (insoles turned on either during the first half or the second half of each trial). Most importantly for our analyses, they found two significant vibrations by task interaction effects for individuals with DN (for mean velocity and for velocity AP) and none for C. Individuals with DN reduced their CoP sway with the vibration while C did not do so.

4. Discussion

As many authors in literature, we believe that peripheral sensory neuropathy is the primary cause of postural instability in individuals with DN. However, this review reveals that peripheral neuropathy may not be the only fundamental cause of significant increased postural sway in individuals with DN. The discussion below highlights potentially relevant additional causes of increased body sway in individuals with DN.

4.1. Evaluation of the peripheral sensory neuropathy hypotheses

In the previous literature, results testing the 3rd expectation were ambiguous, however consistent with the first two expectations. The reviewed studies systematically showed that individuals with DN sway more than C with EO on a firm surface. Moreover, the increase in sway was significantly greater in individuals with DN than in C when their visual information or their vestibular information was perturbed. Therefore, in life conditions with low light or during head rotation, individuals with DN may be quite destabilised, probably to the point of being at a risk for a fall.

Results in literature were not consistent with the 4th expectation because individuals with DN sway more than C in sway-referenced conditions (Di Nardo et al., 1999; Simmons et al., 1997). Therefore, individuals with DN may have other problems, in addition to peripheral sensory neuropathy, that disrupt their posture. Findings in relation to the 1st and the 2nd assumptions are consistent with such an interpretation because individuals with DN were shown to be quite unstable in stance.

4.2. Additional reasons explaining individuals with DN instability

Not many disease-related impairments could explain the revealed increased postural sway in individuals with DN. Indeed, it is important to recall that the population under investigation was selected under an extended list of inclusion/exclusion criteria (see method). In reviewed studies, two factors were not deeply related to postural sway, that is, visual impairments and changes in postural coordination.

In the reviewed studies, only three authors excluded participants with visual impairments (Corriveau et al., 2000; Schilling et al., 2009; Yamamoto et al., 2001). Only Simoneau et al. (1994) conducted analyses on visual acuity, loss of binocular vision, and presence of double vision. These analyses did not show that visual impairments can increase DN CoP sway. However, the question can be asked whether Simoneau et al.'s (1994) few analyses are sufficient to exclude the factor vision as a fundamental cause of increased postural sway in individuals with DN. Indeed, healthy individuals with visual impairment exhibit significant increased postural sway (Ray and Wolf, 2008). Moreover, many visual problems such as diabetic retinopathy (most important cause of blindness and low vision), cataract, or glaucoma can appear soon in diabetes, even sooner than neuropathy (Zhang et al., 2008). Individuals with diabetes have 60% and 170% more chance to have correctable and un-correctable visual impairments than C (Zhang et al., 2008). Such discussion thus underscores the need for researchers to check relationships between visual impairment and postural sway in individuals with DN.

In the reviewed studies, only three authors directly and deeply studied if individuals with DN adopt a different postural coordination than C with COP/body sway data (Giacomini et al., 1996; Lafond et al., 2004; Simmons et al., 1997). In the ML axis, individuals with DN were shown to be significantly impaired at the level of their inversion/eversion postural control mechanism but not at the level of their load/unload mechanism (Lafond et al., 2004). Since the inversion/eversion mechanism does not have a fundamental role in controlling ML postural sway (Winter et al., 1993), individuals with DN may not exhibit any change in ML postural coordination. However, in the AP axis, Giacomini et al. (1996) and Simmons et al. (1997) both showed that individuals with DN preferred adopting a proximal control – at the level of the hip (Fig. 1B) – than a distal control at the level of the ankle (Fig. 1A). These findings are logical and functional because individuals with DN are expected to have available postural control mechanisms at the level of the hip and disease-impairments at the level of the ankle (neuropathy is peripheral first, cf., Cavanagh et al., 1993). Among other peripheral

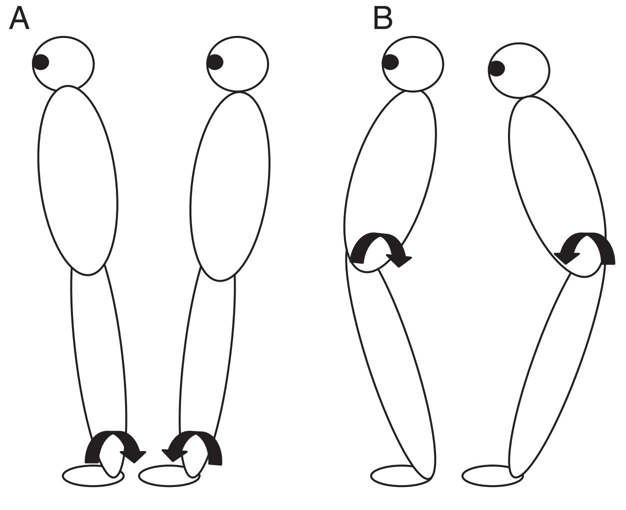

Fig. 1. Postural control mechanisms in the antero-posterior axis. A. The Ankle strategy (Nashner & McCollum, 1985) with rotation of the body essentially around the ankle (as an inverted pendulum); B. The *Hip strategy* with rotation of the body essentially around the hip (Nashner & McCollum, 1985).

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impairments, individuals with DN can have reductions in ankle proprioception thresholds; they can have bone deformations and lack of force among other disabilities (Bonnet et al., 2009). Future studies will need to investigate whether changes in AP postural coordination in individuals with DN are related to their increased postural sway.

Researchers should continue to test practical means that can help individuals with DN to improve their postural stability. Greene et al. (1990) revealed that neuropathy at the hands is less pronounced than neuropathy at the feet. Also, stimulations at the hand are quite effective in reducing postural sway in healthy individuals (Clapp and Wing, 1999; Jeka and Lackner, 1995). Accordingly, hand facilitators may have been more beneficial than feet facilitators in reducing postural sway in individuals with DN. However, our review of the literature showed the contrary effect. This unexpected finding may be explained in three ways. First, DN participants in Dickstein et al. (2001, 2003) were said to be deeply affected by their peripheral neuropathy while DN participants were moderately affected by their peripheral neuropathy or younger (40 to 60 years) – and potentially less affected – in Priplata et al. (2006) and Hijmans et al. (2008), respectively. Second, the kind of facilitator was different in Dickstein et al. (2001, 2003) versus Priplata et al. (2006) and Hijmans et al. (2008). It may be that infraliminary stimulations under the fingertip can reduce body/CoP sway in individuals with DN more than in C. Third, may be that reduced variations of applied mechanical force at the level of the hand are undetectable, while great amount of mechanical variations under the feet (supporting body weight) can be picked-up. Future investigations are necessary to investigate these questions. Until today, the findings show that the better way for individuals with DN to improve their postural stability is to receive infraliminary stimulations under their feet.

5. Conclusion

The present review showed that individuals with DN are more destabilised in posture than what is expected as a consequence of their peripheral sensory neuropathy. It proposed that visual impairments and/or changes in postural coordination may be additional fundamental reasons explaining their increased postural sway. Future studies will need to control/test these additional factors. At the practical level, there is a great need to find ways to reduce postural instability in individuals with DN. In this regard, experiments with different kinds of facilitators need to be pursued, either passive ones (e.g., changes in medication, footwear devices, and sound signalling excessive postural sway) or active ones (e.g., training programs to improve muscle strength, extension capabilities, kinaesthesia, and proprioception).

Conflict of interest

All the authors have nothing to disclose.

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