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RESEARCH ARTICLE

Arterial baroreflex modulation influences postural sway

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Abstract
Objective Although considered mainly a random function, postural sway is influenced by physiological factors such as respiration. A direct effect of the autonomic nervous system (ANS) on posture has never been demonstrated. To test this hypothesis, we used a pure motion-independent autonomic stimulus (neck suction) to modulate the carotid baroreceptors on a broad frequency range, distinct from that of respiration.
Methods Thirteen healthy subjects (age 26 ± 5 years) were studied upright, eyes closed, and on a force platform during controlled breathing (15 breath/min, 0.25 Hz), with and without stimulation of arterial baroreceptors by sinusoidal neck suction (0 to −30 mmHg pressure) at different frequencies (0.05, 0.10, 0.125, 0.15, 0.175, 0.20, 0.30 Hz), for eight periods lasting 2 min each. The increase in sway, R–R interval and blood pressure induced at each stimulation frequency was measured by spectral analysis.
Results With neck suction, we observed a significant ($p < 0.05$) increase in oscillations synchronous in the R–R interval (from 0.10 to 0.20 Hz), systolic and diastolic blood pressure (from 0.05 to 0.15 Hz) and sway (from 0.10 to 0.30 Hz in both the antero-posterior and medio-lateral planes). Changes were greater in the left than in the right foot.
Conclusion Our study shows that postural sway is modulated by the ANS and is influenced by phasic stimulation of the arterial (carotid) baroreceptors. Our findings have potentially important clinical implications in the development of treatment strategies for pathological conditions in which alterations in posture and autonomic function coexist and could be mutually influenced.

Keywords Posture · Autonomic nervous system · Arterial baroreceptors

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Introduction

The maintenance of an upright posture in man is a dynamic motor skill that requires control and co-ordination of several mechanisms. Pressoreceptors on the foot sole provide exteroceptor information [17]; proprioceptive receptors located in muscles, tendons and joints contribute to the adjustment of muscle length [11, 21, 27, 29]. Signals from visual, vestibular and central nervous systems are also essential to postural control.

In the upright posture there is a continuous sway of body, which has been interpreted as a stochastic movement of the centre of body mass [7]. However, there is also evidence that postural sway is conditioned by physiological factors such as respiration [5, 12, 13, 15, 26], dynamic body fluids and internal shift of masses [14]. The relationship between posture and autonomic nervous system (ANS) has been addressed somehow, showing that postural changes affect the autonomic control of cardiovascular and respiratory parameters [25, 26, 28]. Thus far, a direct effect of the ANS on posture has never been demonstrated. To test this hypothesis, it is necessary to use a pure autonomic stimulus, such as carotid sinus baroreceptor stimulation, which, unlike respiration, is motion independent.

Activation of carotid sinus baroreceptors can be achieved by applying an external suction to the neck [2–4, 10]. Sinusoidal stimulation, rather than single pulses or transitions, offers several advantages: it does not produce startle reactions or movement artefacts, can be administered through a wide frequency range (0.05–0.30 Hz) and can be easily separated from the influence of respiration (because suction of the neck and respiration can be set at separate frequencies). Moreover, in our experience, it is well tolerated and, if different stimuli are presented in a randomised order, it reduces the possibility of fatigue error to a minimum, especially during short-lasting experiments.

In the present study, we used neck suction (NS) to test whether body sway is influenced by the ANS via stimulation of arterial baroreceptors and is modulated by a preferred frequency of an autonomic stimulus. Providing evidence that the ANS influences postural sway could have clinical implications in diseases in which alterations in posture and autonomic function coexist and could be mutually influenced.

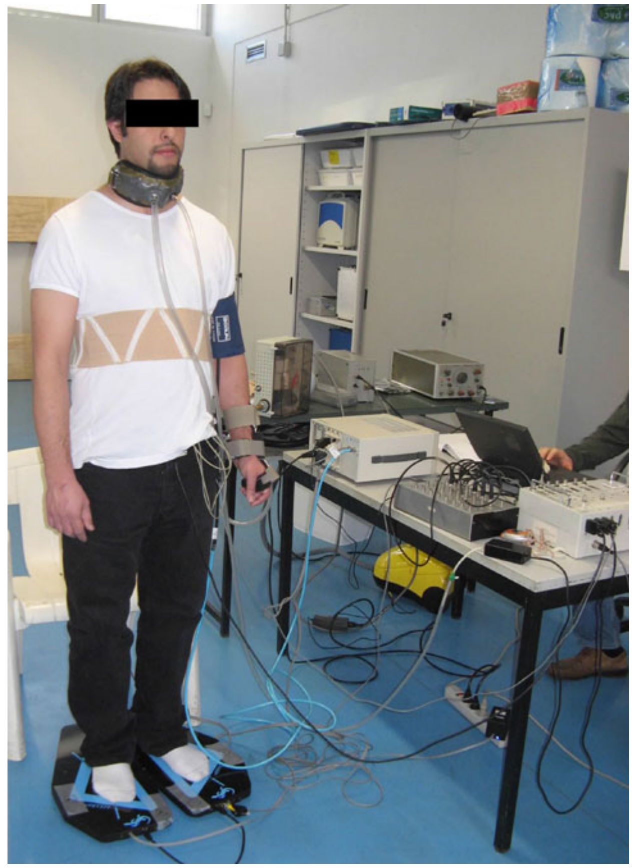

Fig. 1 Healthy subject during anterior neck suction. Baroreceptor stimulation was obtained by a flexible, moulded lead neck collar connected to a vacuum pump. During each recording electrocardiogram (lead II), respiration (by inductive plethysmographic band), postural sway (platform pressure sensors), blood pressure (Portapres©, FMS, Amsterdam, The Netherlands) and pressure within the neck collar during baroreceptor stimulation (by Statham P23d pressure transducer) were monitored

Methods

Subjects

Thirteen healthy young adults (8 male, 5 female, age 26 ± 5 years, height 171.62 ± 9.22 cm, weight 69.85 ± 14.5 kg and BMI 23.49 ± 3.14) volunteered for this study. The protocol was approved by the local ethics committee. All subjects gave their informed consent.

Protocol

Subjects were studied in the upright position, with their feet on a force platform (Fig. 1) (Lizard med, Como, Italy, http://www.lizardmed.eu/index.php) consisting of two independent boards, underneath which were three pressure sensors individually amplified. Postural sway signals were recorded from two horizontal planes, antero-posterior (left, right, total) and medio-lateral (left, right, total).

All eight different recordings, lasting 2 min each, were obtained with the subjects keeping their eyes closed. They were asked to control their breathing at 15 breath/min to maintain the respiration frequency strictly confined to 0.25 Hz: this eliminates a possible interference of respiration with NS.

A baseline recording was the control condition. Seven NS recordings, each with stimulation at one of seven different frequencies (0.05, 0.100, 0.125, 0.150, 0.175, 0.200 and 0.300 Hz), were performed in a random order with an inter-stimulus interval of a minute.

During each recording, the following signals were monitored: electrocardiogram (lead II), respiration (inductive plethysmographic band), postural sway (platform pressure sensors), blood pressure (BP) (Portapres©, FMS, Amsterdam, The Netherlands) and pressure within the neck collar during baroreceptor stimulation (Statham P23d pressure transducer).

Baroreceptor stimulation

NS was applied to a flexible, moulded lead neck collar placed on the anterior neck region, connected to a vacuum pump [3, 4, 10]. A computer-controlled rotary valve, previously designed and built in our laboratory [10], provided a sinusoidal suction profile for pressure ranging from 0 to −30 mmHg. The sinusoidal change in (negative) pressure imposed at the neck activates and deactivates the carotid baroreceptors. A low frequency stimulus (0.1 Hz) is transmitted to BP and R–R interval; a higher frequency stimulus (0.2 and 0.3 Hz) is transmitted to the R–R interval but not to BP [3], although it is well evident in the sympathetic nerve traffic [4]. The following response is quantified by the increase in oscillatory component induced on the target signal with respect to a control condition (no-neck suction). As for the cardiovascular parameters, if postural sway responds to NS stimulation, this would be evidence of autonomic modulation on sway.

In addition, to test whether just the simple sensation of neck collar pressure could modify sway, in a subset of four subjects baroreceptor stimulation was applied by positioning the collar at the back of the neck, leaving the anterior part of the neck (where baroreceptors are located) unaffected.

Data analysis

Analogue signals were sent to an analogue digital converter (12-bit resolution, sampled at 300 Hz/channel) connected to a personal computer (Macintosh, Apple, Coupertino, USA) via serial interface. A computer program written in "C" was used to obtain the parameters in a time series format. The original signals and time series were stored and later subjected to spectral analysis. From the six platform sensor raw signals, the shifts of centre of pressure (measured in mm) for whole body, and right and left foot were obtained.

Power spectrum analysis to R–R interval, respiratory, systolic and diastolic BP, body sway and NS signals were applied using an autoregressive model. This method has the advantage of giving reliable estimates of the power associated with peaks at various frequencies using a relatively small amount of data and is able to provide a better identification of the frequency of each significant peak [3, 4]. For each signal, the power in the oscillations at each of the seven stimulation frequencies during NS was compared with the spontaneous oscillations at those same frequencies without NS. In addition, the coherence between NS and sway signal was analysed using a bivariate autoregressive spectral method [4] to test whether the oscillations seen in sway were statistically linked to the stimulus. A coherence value equal to or greater than 0.5 is traditionally evidence of significant association between oscillations at the same frequency in pairs of signals.

We also tested whether respiration was entrained by NS at each of the different stimulation frequencies, by comparing the respiratory power in the respiratory band and at each of NS stimulation frequency, at baseline and during neck suction.

This analysis was done for all the signals obtained by suction stimulation of the anterior and posterior neck regions.

Statistical analysis

Results are given as mean ± SEM. Due to the skewed distribution of spectral power, spectral data were analysed after natural logarithmic transformation. Analysis of variance for repeated measures on two levels was performed to test the effects of frequencies and NS versus baseline. When statistical significance was obtained, Student's t test (paired), Fisher PLSD and Sheffe tests were applied to test the effects of NS at each frequency and for each signal. Similar tests were carried out to test the left/right foot differences at baseline or during NS on sway signals. The level of significance was set at $p < 0.05$.

Results

Respiration

Baseline

As expected, the respiratory signal showed the main activity at 0.25 Hz. However, a secondary peak was observed at half the frequency (0.125 Hz) (Fig. 2). No other conspicuous activities were noted at other frequencies. Thus, although respiration was strictly controlled, a minor but evident effect (clearly a sub-harmonic of respiration) remained evident at 0.125 Hz. This effect was not seen in other signals. Therefore, it cannot be attributed to the mathematical technique used, but it could have been influenced by the thumping effect of the heart on the respiratory belt.

Effect of anterior neck suction

Respiration remained confined at 0.25 Hz, with no additional power at other frequencies, except the 0.125 Hz effect already seen at baseline. The power and frequency distribution of respiration did not change during NS (Fig. 2) as compared to baseline, thus excluding that respiration could have been entrained by NS.

Cardiovascular parameters

Baseline

R–R interval, and systolic and diastolic BP showed spontaneous oscillations with a peak at 0.1 Hz (Fig. 3), typically seen in healthy subjects in the upright position. The

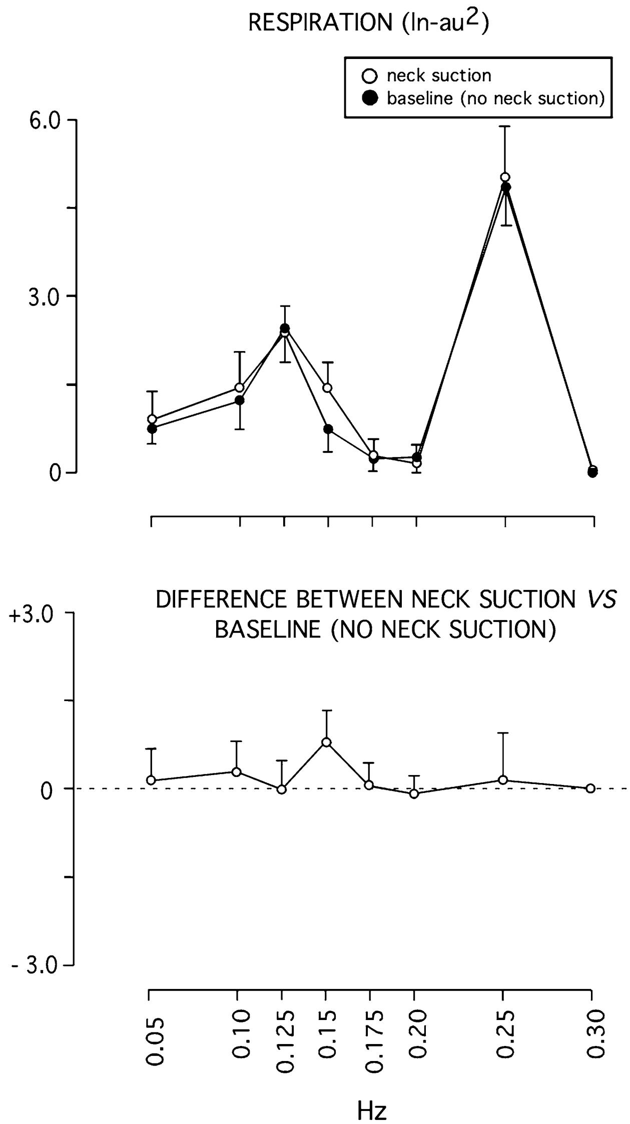

Fig. 2 Test for the effect of neck suction on the respiratory signal (Arbitrary Units, au; mean ± SEM). Because respiration was controlled at 0.25 Hz (i.e. different from the frequency of neck suction stimulation), only minor non-significant differences were observed between data recorded at baseline and during neck suction. In addition, the largest power remained confined to 0.25 Hz, demonstrating that respiration was not entrained by neck suction. However, a second peak in respiration was clearly seen at 0.125 Hz, indicating a sub-harmonic of respiration. Again, this was not influenced by neck suction, as it also occurred at baseline and was not increased by neck suction

spontaneous oscillations were evident up to 0.15 Hz for R–R interval, and systolic and diastolic BP.

Effect of anterior neck suction

R–R interval oscillations increased at all stimulation frequencies, and a peak oscillation was observed at 0.1 Hz. NS also increased the oscillations in systolic and diastolic BP, but mainly in the lower frequencies, peaking at 0.1 Hz. No effect was observed at the frequencies beyond 0.175 and 0.15 Hz, for systolic and diastolic BP, respectively (Fig. 3). The maximum increase in BP oscillations occurred at the lower frequencies (systolic BP at 0.1 Hz, diastolic BP at 0.05 Hz). The R–R interval showed the largest effect of NS at 0.15 Hz.

In all cardiovascular signals, a component synchronous with respiration was present at 0.25 Hz. However, in all signals the power of this component remained unchanged from baseline to NS (histograms in Fig. 3).

Posterior neck suction

No differences were seen with baseline.

Body sway

Baseline

In both the antero-posterior and medio-lateral planes, peak spontaneous oscillation activity occurred at 0.125 Hz, with spontaneous oscillations at 0.1 Hz. The oscillations were significantly larger in the left than in the right foot (Fig. 4).

Effect of anterior neck suction

NS increased the spontaneous oscillations at nearly all frequencies. NS oscillations showed significant coherence with sway oscillations at the same frequency. One peak was found at 0.1 Hz (antero-posterior left, medio-lateral left and medio-lateral right) and at 0.125 Hz (antero-posterior right and whole body, and for medio-lateral plane whole body) (Fig. 4). The effect of NS was lower at the frequency immediately higher than this first peak and showed a progressive increase with higher frequencies. The highest effect of NS was evident at the highest frequency of stimulation (0.30 Hz).

In all sway signals, a component synchronous with respiration was present at 0.25 Hz; however, the power of this component remained unchanged from baseline to NS (histograms in Figs. 3, 4).

In all the conditions, except medio-lateral total, a peak difference was noticed at 0.10 Hz followed by a trough and an increasing difference with increasing frequency of stimulation, so that the maximum differences occurred at the highest frequency of stimulation (0.30 Hz) (Fig. 5).

Figure 6 provides an example of autoregressive power spectra analysis of cardiovascular and postural sway signals obtained with NS at 0.10 Hz in one of the subjects.

There was no coherence between systolic BP and NS at 0.30 Hz stimulation, whereas it was high at 0.10 Hz (0.66 ± 0.08). Coherence between sway and NS was

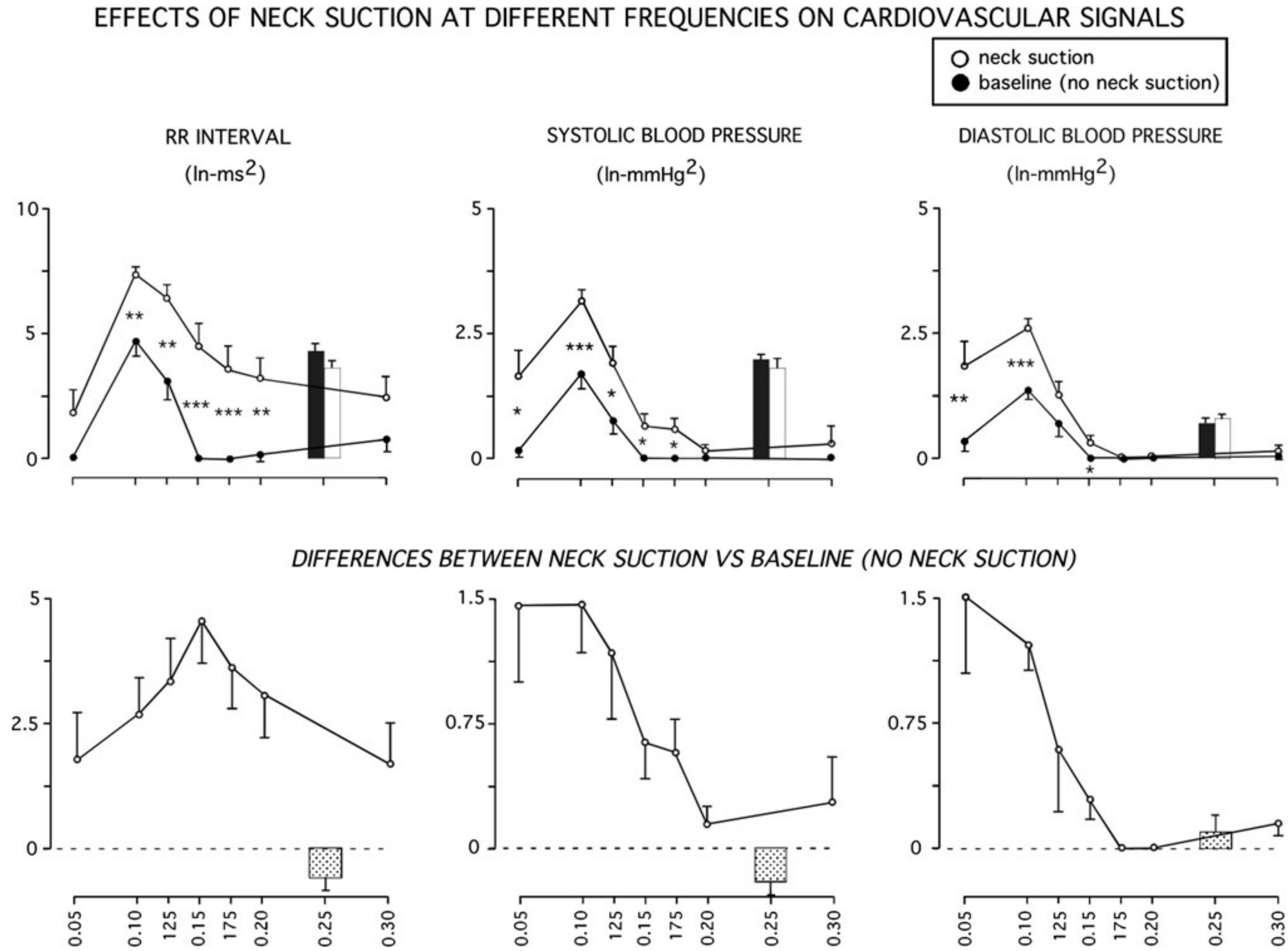

Fig. 3 Effect (mean ± SEM) of anterior neck suction at different frequencies on R–R interval, systolic and diastolic BP. In the *top panels*, the *white circles* represent the power of fluctuations during neck suction at each frequency of stimulation; the *black circles* represent the baseline (no-neck suction) power of fluctuations at the same frequencies of those of neck suction stimulation. Differences between neck suction and baseline are marked by *asterisks* (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$). The *bottom panels* show the difference between baseline and neck suction at each frequency. At baseline all signals show the typical marked prevalence in spontaneous oscillations at 0.1 Hz of healthy subjects when upright. Neck suction increases all oscillations in the R–R interval and only low frequency oscillations in BP. Therefore, whilst R–R interval shows an all-pass response (*bottom panel*, *left*), with a peak around 0.15 Hz, BP responds only as a low-pass system, with almost no response above 0.15 Hz (*bottom panel*, *centre* and *right*). The *histograms* represent the effect of respiration (which was fixed at 0.25 Hz) on each sway signal at baseline (*black histogram*) and during neck suction (this was averaged for each subject over the six neck suction stimulations, *white histogram*) in the *top panels*, and the changes induced by neck suction in the respiratory band of each signal in the *bottom panels*

higher at 0.30 Hz than at 0.10 Hz (0.69 ± 0.05 vs. 0.58 ± 0.11). During 0.10 Hz stimulation, the phase between NS and sway was +2.71 ± 0.21 radians (NS leading sway) and +2.25 ± 0.11 radians between NS and systolic BP, which was significantly shorter ($p < 0.05$, Wilcoxon test). During 0.30-Hz stimulation, the phase between NS and sway was +2.33 ± 0.50 radians.

Posterior neck suction

When NS was applied to the posterior part of the neck (baroreceptor-free area), the above findings could not be replicated in the postural sway or in the cardiovascular signals. This confirms that the effects obtained with NS applied to the anterior part of the neck were indeed due to stimulation of the carotid baroreceptors.

Although neck proprioception could have an influence on postural sway, the results of our study eliminate this possible confounder.

Discussion

To the best of our knowledge, our findings demonstrate for the first time that postural sway can be modulated by stimulation of the arterial baroreceptors, thus indicating

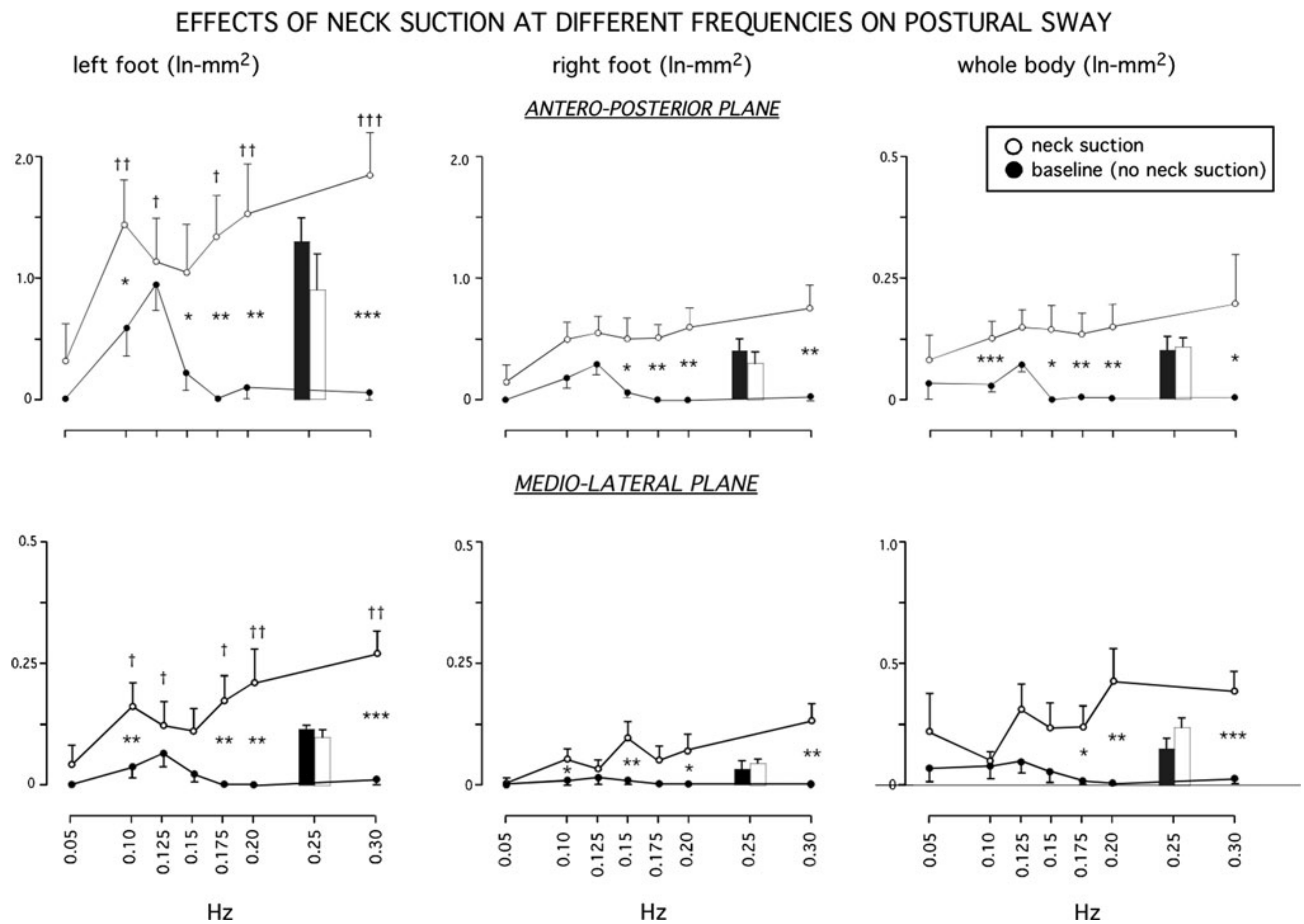

Fig. 4 Effect (mean ± SEM) of anterior neck suction at different frequencies on postural sway, in the antero-posterior and medio-lateral planes, for the right and left foot, and for the whole body. *White circles* represent the power of fluctuations in sway during neck suction, at each frequency of stimulation. *Black circles* represent the baseline power of fluctuations at the same frequencies as those of neck suction stimulation. The *histograms* represent the effect of respiration (which was fixed at 0.25 Hz) on each sway signal at baseline (*black*) and during neck suction (*white*). Differences between neck suction and baseline (no-neck suction) are marked by *asterisks* (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$), whereas differences between left and right foot are marked by crosses ($^{\dagger}p < 0.05$, $^{\dagger\dagger}p < 0.01$, $^{\dagger\dagger\dagger}p < 0.001$). (1) Neck suction induced marked effects in all signals, particularly at 0.1 Hz and higher frequencies of stimulation (2) both spontaneous sway and the effect of neck suction were much greater on the *left* than *right side*

that postural sway is influenced by the autonomic nervous system. Our results also show that postural sway is responsive to stimuli at low frequency (0.1 Hz) and tends to respond increasingly at higher frequencies of stimulation (0.2 and 0.3 Hz): this behaviour seems compatible with that of a sympathetic modulation.

It has been observed that respiratory motion is actively compensated by postural adjustment through reflex mechanisms and modulation by areas in the central nervous system connected with the respiratory control [12] indirectly suggesting that the ANS might also have a role in postural control. By applying a previously validated methodology [3], we observed that NS was able to induce oscillations in postural sway at several different frequencies confirming that body sway can be modulated directly by an autonomic stimulus originating from the arterial baroreceptors. NS stimulus was more effective at specific frequency bands, particularly at 0.1, 0.2 and 0.3 Hz. This definite trend argues against the possibility of a mechanical motion of the subject induced by the sensation of suction, as this would have been different in different subjects, thus creating a non-consistent pattern of response.

In agreement with previous findings [5, 12, 13, 15, 18, 23], the respiratory signal was always present on sway signals, in both antero-posterior and medio-lateral planes (Figs. 4, 5). Due to the strict control (at 0.25 Hz, 15 breath/min) of the breathing frequency, the power in the spectrum of the respiratory signal was essentially confined to the 0.25 Hz region, with the exception of a sub-harmonic that was observed at 0.125 Hz (half frequency of breathing). During NS, the respiratory signal remained confined to these frequency regions, and the power did not increase (Fig. 4).

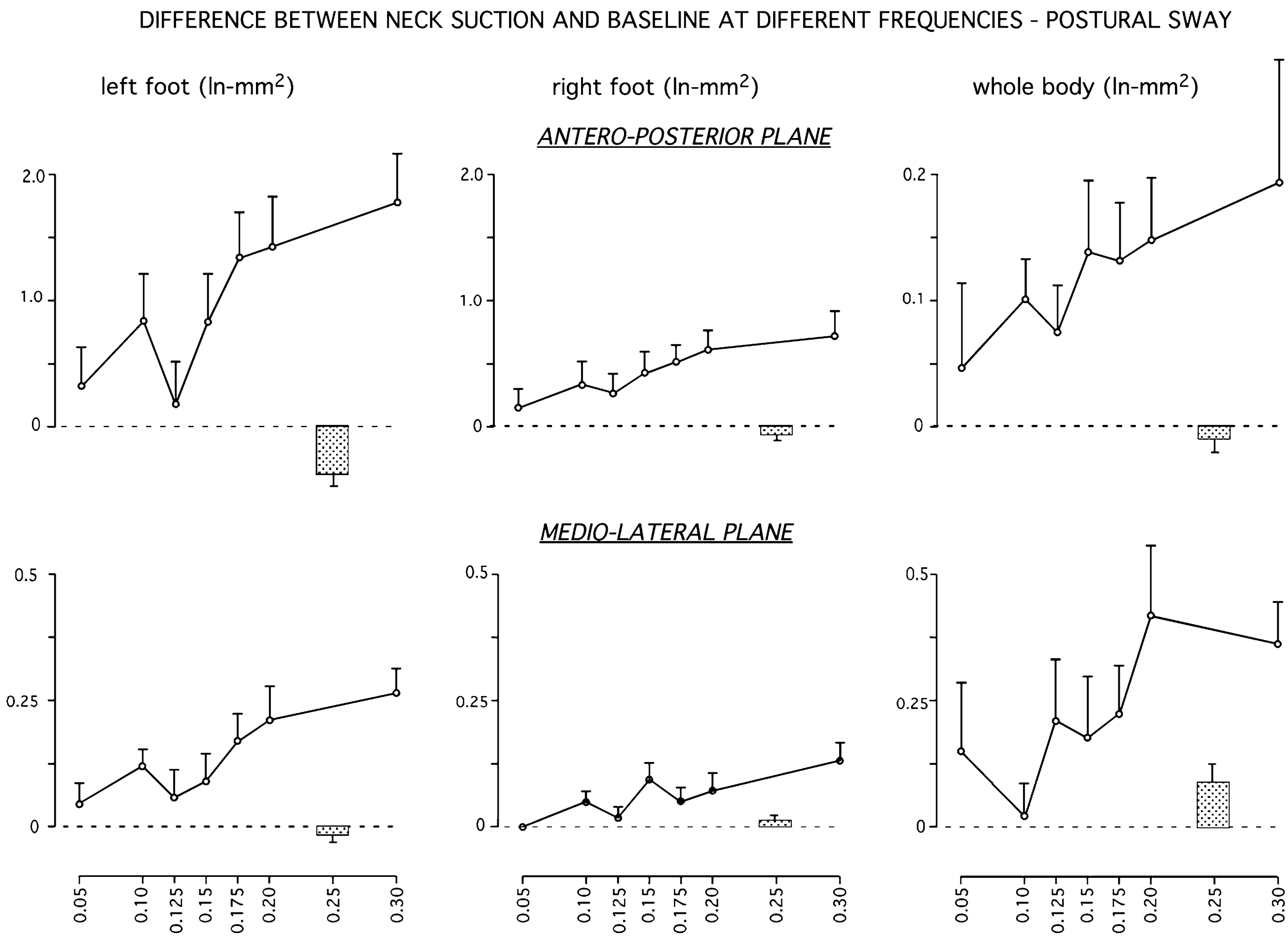

Fig. 5 Differences in sway oscillations induced by anterior neck suction at each frequency of stimulation, in the antero-posterior and medio-lateral planes, for the right and left foot, and for the whole body. Note that in response to neck suction, all sway signals show a high pass behaviour, and a separate peak at 0.1 Hz (except for medio-lateral plane—whole body, in which this peak occurs at 0.125 Hz). The *histograms* represent the changes induced by neck suction in the respiratory band of each signal

These findings confirm that in our experiment respiration was not entrained by (and mixed with the effect of) NS.

Our observations indicate that body sway (both in the antero-posterior and medio-lateral planes) oscillates at specific frequencies of NS stimulation. A peak oscillation was seen at the frequency of 0.1 Hz followed by a slight fall, and then by a progressive increase in response with higher frequencies (0.2 and 0.3 Hz), similar to what we previously observed in muscle sympathetic nerve activity (MSNA) [4]. This pattern was more evident in the antero-posterior plane, and on the left side. The first peak of oscillation occurred at 0.1 Hz and coincides with the frequency of the Mayer waves, which are considered marker of sympathetic modulation in the systemic circulation [2, 16]. In support of this hypothesis, we found that R–R interval and BP showed a peak of response at this same frequency. In previous studies [4], we found that BP responds only at this frequency band, whilst the R–R interval is responsive to baroreceptor modulation over a much broader frequency range. In the present study due to the upright posture, a condition known to enhance sympathetic activity, the peak response around 0.1 Hz, was more evident (Figs. 3, 4, 5). By analogy with the cardiovascular signals, it is thus likely that the presence of this 0.1 Hz peak in the upright postural sway can be regarded as an evidence of sympathetic modulation.

Anatomical and functional connections between vestibular and autonomic systems contribute to postural sway control [1, 20, 24, 30]; yet, a connection between continuous postural adaptations and autonomic modulation has not been tested. Previous studies using NS reported that artificially increased baroreceptor activation is associated with inhibition of the stretch reflex [9, 22], suggesting a relationship between these structures, possibly through modulation of reticular formation neurons by the baroreceptor integration nucleus [22]. The baroreceptor modulation of sway signal that we showed in the present study could be one aspect of the interaction between structures

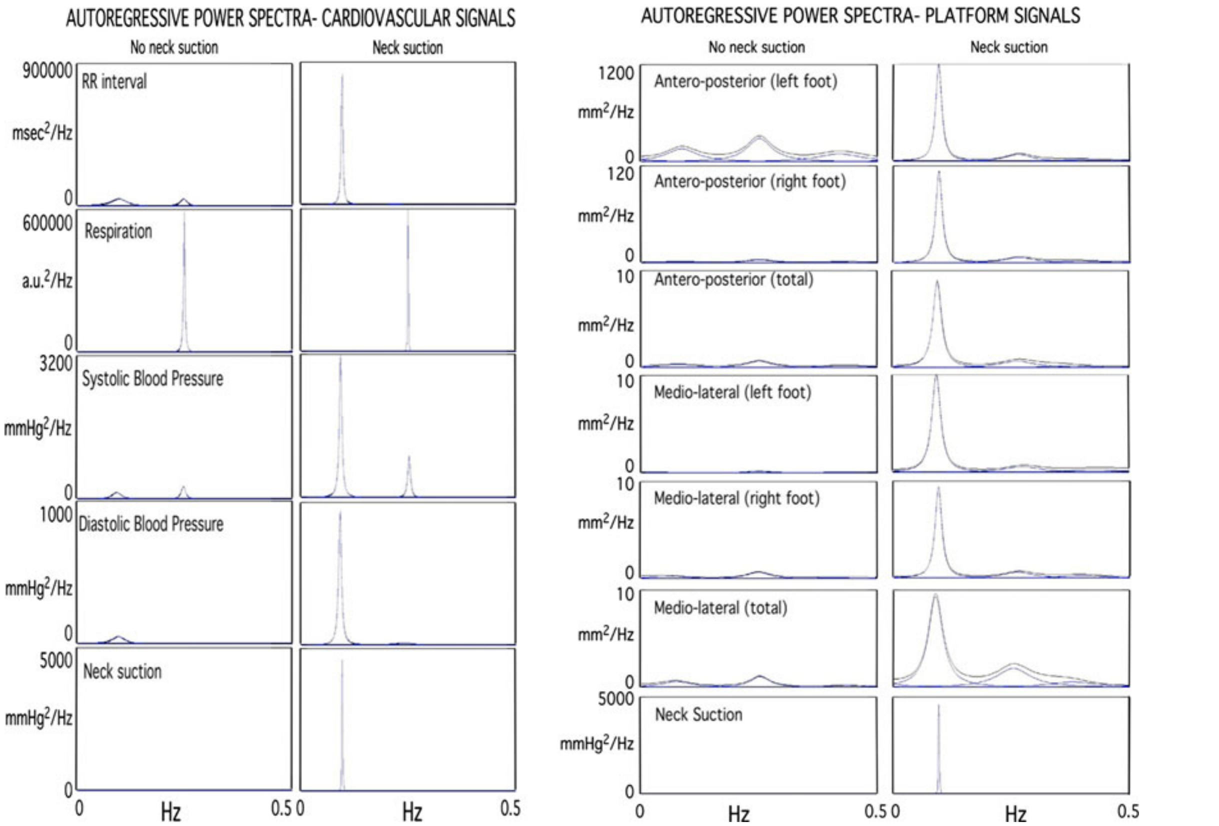

Fig. 6 Example of autoregressive power spectra analysis of cardiovascular and postural sway signals obtained with neck suction at 0.1 Hz in one of the subjects. The *left panel* shows the power spectra of the R–R interval, respiratory, systolic and diastolic blood pressure signals at baseline (no-neck suction) and during neck suction. Following responses of R–R interval, systolic and diastolic blood pressure are evident. The *right panel* shows the power spectra of the postural sway signals recorded from the anterior–posterior (left foot, right foot and total) and form the medio-lateral (left foot, right foot and total) planes at baseline (no-neck suction) and during neck suction. The following responses of all the postural sway signals are evident

controlling posture and those involved with cardiovascular system regulation. Our findings are in agreement with those observed by other authors when a rhythmic stimulus showed a stabilizing effect on posture [19] or when studied in the context of a more complex phenomenon such as orthostatic hypotension [6]. Of note is that our results were obtained comparing baseline with NS whilst maintaining the upright position; therefore, no orthostatic stress effect could have interfered with the changes observed in respiratory, cardiovascular or postural sway measurements. This further corroborates our hypothesis that a pure autonomic stimulus, such as arterial baroreflex modulation, influences postural sway.

An unexpected finding of the present work was a marked difference in the symmetry of sway (left vs. right side) and in the effect of NS modulation in the antero-posterior and medio-lateral planes. This suggests that NS modulation induced an asymmetrical rotation. The evidence of an asymmetry at baseline and in response to NS (Figs. 4, 5) could be further evidence of an asymmetrical control of posture, suggesting that the same mechanism works both at rest and under autonomic stimulation. Interestingly, the asymmetry we observed in response to NS could be in accordance with the previous finding [4] that stimulation of the right baroreceptor has a dominant effect over the left baroreceptor in controlling heart rate (hence the sinus node), suggesting incomplete crossing of autonomic reflexes.

Limitations

MSNA could have provided direct evidence of sympathetic traffic, but this technique is not reliable in the free upright posture.

Unlike our previous work [10], in the present study we used a single neck chamber to stimulate both right and left baroreceptors simultaneously and did not study the separate effect of right versus left stimulation, which will warrant further studies.

Fatigue during the experiment could be seen as a confounding factor. However, the short duration, the random stimulus sequence and the fact that heart rate and BP were similar at the beginning and at the end of the study assured that fatigue was not an issue.

In theory, the motion of the heart and its autonomic modulation could have affected the sway signal (ballistocardiographic-like effect). However, such vibrations remain confined within the systolic part of the heart beat and are much smaller than the sway signal, thus requiring averaging [8]. This interference is therefore unlikely in the present study.

Conclusion

The present study shows that postural sway is modulated by the autonomic nervous system and is influenced by phasic stimulation of the arterial baroreceptors.

The asymmetry observed between sway of the right versus left foot, together with the asymmetry of sway in the antero-posterior and medio-lateral planes, may be evidence of a strategy to maintain posture through a rotational motion. Baroreflex modulation is yet "another" mechanism influencing postural sway.

The present findings may help understand the pathophysiology of conditions in which alterations in posture and autonomic function coexist and could be mutually influenced. Furthermore, our findings that the ANS is implicated in the control of posture have potential important clinical implications that could help develop treatment strategies for patients with postural and ANS-related problems.

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