Physiological interdependence of the cardiovascular and postural control systems under orthostatic stress

Amanmeet Garg, Da Xu, Alexandre Laurin, and Andrew P. Blaber

1School of Engineering Science, Simon Fraser University, Burnaby, British Columbia, Canada; and 2Aerospace Physiology Laboratory, Department of Biomedical Physiology and Kinesiology, Simon Fraser University, Burnaby, British Columbia, Canada

Submitted 12 March 2014; accepted in final form 16 May 2014

Garg A, Xu D, Laurin A, Blaber AP. Physiological interdependence of the cardiovascular and postural control systems under orthostatic stress. Am J Physiol Heart Circ Physiol 307: H259–H264, 2014. First published May 23, 2014; doi:10.1152/ajpheart.00171.2014.—The cardiovascular system has been observed to respond to changes in human posture and the environment. On the same lines, frequent fallers have been observed to suffer from cardiovascular deficits. The present article aims to demonstrate the existence of interactions between the cardiovascular and postural control systems. The behavior of the two systems under orthostatic challenge was studied through novel adaptations of signal processing techniques. To this effect, the interactions between the two systems were assessed with two metrics, coherence and phase lock value, based on the wavelet transform. Measurements from the cardiovascular system (blood pressure), lower limb muscles (surface electromyography), and postural sway (center of pressure) were acquired from young healthy adults (n = 28, men = 12, age = 20–28 yr) during quiet stance. The continuous wavelet transform was applied to decompose the representative signals on a time-scale basis in a frequency region of 0.01 to 0.1 Hz. Their linear coupling was quantified through a coherence metric, and the synchrony was characterized via the phase information. The outcomes of this study present evidence that the cardiovascular and postural control systems work together to maintain homeostasis under orthostatic challenge. The inferences open a new direction of study for effects under abnormalities and extreme environmental conditions.

THE ORTHOSTATIC CHALLENGE experienced in daily life can lead to serious adverse outcomes in some populations. Orthostatic hypotension and postural instability frequently occur in the elderly (26, 27), patients with neurodegenerative diseases (5), and astronauts (9, 32) and in many cases occur concurrently. Orthostatic and postural reflexes in day-to-day life involve complex interaction between multiple physiological systems to maintain homeostasis and stability. Standing reduces blood pressure (BP) above heart level (e.g., the brain), which is mitigated by baroreflex regulation manifested by increased heart rate, cardiac contractility, and peripheral vascular resistance (30). Additionally, during prolonged standing, contractions of the skeletal musculature play a critical role to maintain BP. These contractions compress the underlying veins, which lead to the pumping of venous blood pooled in the lower limbs back to the heart (i.e., skeletal muscle pump). Absence of this compressive action may lead to fainting under prolonged standing and requires further study. While studies have observed that maintenance of postural orientation integrates sensory information from a wide variety of sources including somatosensory, visual, and vestibular pathways to make appropriate balance corrections through musculoskeletal activation (12), the skeletal muscle pump activation has been shown to be essential to maintain venous return and BP during standing (18) and after exercise (10). These observations suggest that postural orientation control may very well integrate information from BP in addition to known balance variables.

It has been known from past observations that leg movement while standing upright helps maintain BP (30). Only recently has research been conducted to investigate the control relationship between the skeletal-muscular and cardiovascular systems. A conceptual model of cardiac-locomotor coupling was recently proposed where, as a result of the force generated by muscle contraction during walking, the skeletal muscle group acts as a pump, rhythmically propelling venous blood to the right atrium (28). Claydon and Hainsworth (11) revealed that certain individuals with poor orthostatic tolerance with a tilt test but no history of syncope or presyncope had increased postural sway in upright stance, which most likely enhanced venous return and prevented fainting. The potential interaction between BP and postural sway has also been investigated in terms of their relationships to lower limb and trunk discomfort (1). These studies suggest the presence of compensatory mechanism via the activation of skeletal muscle pump in cardiovascular regulation. This speaks to the importance of an integrated BP and postural control system, particularly with poor or impaired vascular control.

Based on our observations of the correlation between postural sway and BP (3), we have developed a new physiological model that integrates the cardiovascular and postural control systems through the skeletal muscle pump (Fig. 1). In this model we hypothesize a baroreflex-induced interaction between BP regulation and lower limb muscle activation. Subsequent studies based on this model have confirmed the existence of cardiopostural interactions during quiet stance and validated the use of wavelet transform in characterizing the interactions (13, 14). Wavelet transform coherence analysis applied in this study has been in part applied in other physiological investigations (20–23, 33).

The present study is among the first to systematically conduct a quantitative investigation of interactions between the cardiovascular and postural systems during quiet standing. The interdependence was assessed using both signal coherence and synchrony based on wavelet transform. To further distinguish muscle contractions induced by postural adjustments from those initiated by baroreflex, representative signals from the

Address for reprint requests and other correspondence: A. P. Blaber, Aerospace Physiology Lab., Dept. of Biomedical Physiology and Kinesiology, Simon Fraser Univ., 8888 Univ. Dr., Burnaby, BC, V5A1S6, Canada (e-mail: aabajoer@sfu.ca).

http://www.ajpheart.org 0363-6135/14 Copyright © 2014 the American Physiological Society
Cardiovascular system [systolic BP (SBP)], lower limb muscle activation [electromyography (EMG)], and postural sway [center of pressure (COP)] were measured and analyzed. We hypothesized that 1) The three (cardiovascular, posture, muscular) systems interact in a sporadic manner either pairwise or all together, representing different physiological mechanisms; 2) the majority of lower limb EMG activity is associated with postural sway since these two are known to be closely related; 3) baroreflex mediated EMG activation exists and can be observed through interactions between EMG and SBP where other interactions are absent; and 4) the interactions between the systems are frequency dependent within the physiologically relevant range. The hypothesized interactions between the two systems provide a potential for understanding the unexplained system level physiological integration.

METHODS

Protocol and Data Collection

Data were collected from 28 young individuals (12 men, age = 25 ± 2.2 yr, height = 172 ± 9.3 cm, weight = 65 ± 12.4 kg) during a sit-to-stand test. All participants were screened for any cardiovascular disease or postural complications through questionnaire and verbal confirmation. All participants were required to refrain from exercise and caffeine for 24 h before the experiment.

The experiments were conducted in a sensory input-reduced environment within an enclosed space. The participants changed into comfortable clothing before height and weight measurement. After all the physiological monitoring sensors were fixed to the participant, they were seated and checked for foot placement, signal acuity, and general comfort. The sit-to-stand test required the participant to remain seated for 5 min and maintain quiet stance for 5 min after passive-assisted transition from sitting phase. The purpose of this procedure was to challenge the cardiovascular system and monitor responses. This 10-min procedure was conducted blindfolded, and eyes closed with an imaginary eye-level gaze. The eyes-closed condition was selected as postural sway increases with the removal of visual input, which leads to elevated levels of muscle activation and an increased ability to isolate posture and BP related contractions. It is known that visual cues affect sway responses in the studied frequency range (29). Quiet standing on level ground was chosen to minimize modifications of sway effects that are caused by fear of falling (8). The experiment protocol was approved to be of minimal risk by Simon Fraser University’s research ethics board. Written informed consent was obtained from each participant before the experiment.

Throughout the 10-min period, bilateral lower leg EMG was collected from four leg muscles: tibialis anterior, medial gastrocnemius, lateral gastrocnemius, and medial soleus, chosen in accordance with the observations by Joseph et al. (19). Transdermal differential recording of signals was performed using an eight-channel EMG system, (Myosystem 1200, Noraxon, AZ). For signal transduction, Ag/AgCl dual electrodes (2-cm interelectrode distance) were used at the muscle sites, and a single Ag/AgCl electrode was placed at the right lateral malleolus as a reference electrode. The sites of electrode placement were chosen in accordance with the recommendations for placement of electrodes from the SENIAM project (17). Electrocardiography signals were acquired (LifePak 8, Medtronic) using the lead II configuration. Continuous BP measurements were acquired by photoplethysmography using a finger cuff (Finapres, Ohmeda 2300, Ohmeda, OH) and adjusted to heart level via a hydrostatic correction. Postural sway data, in terms of coordinates of the body COP (COPx and COPy), were computed from the force and moment data collected with a force platform (Accusway Plus, Advanced Medical Technologies). Feet were placed in a parallel foot configuration with a distance of 5 cm (measured at the first toe and heel) between them. The data were stored as 16-bit digital, acquired at a sampling rate of 1.000 Hz with a 32-alog input channel DAQ card and Labview 8.2 software (National Instruments).

Data Analysis

The last 4 min of the quiet stance phase were used for analysis. Beat-by-beat time series of SBP were obtained from the maximum pressure values of the BP waveform for each beat identified through the R-wave detection in the electrocardiography signal. Response and control of the overall postural system were the main focus of this study. To this end, aggregate EMG was obtained by addition of rectified, zero-mean, EMG recordings from all individual leg muscles as in previous studies (4, 14). Similarly, the overall resultant COP (COPr) was obtained from COPx (medial-lateral sway) and COPy (anteroposterior sway). All data were resampled to 10 Hz before the application of wavelet transform.

Data analyses were implemented in MatLab (MathWorks, Natick, MA), and the results are presented as means ± SE unless noted otherwise.

Linear coupling. The wavelet transform coherence estimates, ranging from 0 to 1, were obtained through implementation of the method proposed and explained in detail by Torrence and Compo (35). The same value of the wavelet coefficient ($\omega_0 = 6$) for the Morlet wavelet was used throughout the analysis. A cone of (edge) influence (COI) on the time-frequency map, in which the edge effect is considered nontrivial, was defined as described in Grinsted et al. (16) (Fig. 2B). For each signal pair analyzed, 1,000 pairs of surrogate data were generated with a first-order autoregressive process model whose coefficients were estimated from the actual signals. The wavelet coherence was then calculated for all pairs of surrogate data with the coherence threshold set at the 90th percentile of the coherence sampling distribution at each scale/frequency, as established through the Monte Carlo method (16).

Phase synchrony. Phase dynamics derived from wavelet decomposition of the signals indicate system-level interactions, where a close coupling between two signals is characterized by constant or zero difference in phase (i.e., phase lock) (23).

Traditionally, coherence has been used to represent a measure of linear covariance between two signals, combining the effects of signal amplitude and phase in the interrelationship, whereas the phase synchrony has indicated a direct phase relationship. The degree of synchrony between two signals can be quantified through the metric of smoothed phase lock value (S-PLV) (23, 24). Analogous to coher-
Fig. 2. The results from the wavelet coherence and phase analysis between the cardiovascular and postural control system: A: raw data from one participant of EMG and continuous waveform blood pressure (BP). The upper envelope of this tracing is SBP, AU, arbitrary units. B: time-frequency plot (bottom) of wavelet coherence between EMG and SBP signals from A and summary Venn diagrams (top) from 28 subjects’ significant coherence (%SC) in low-frequency (LF) and very LF (VLF) bands. C: same presentation of results as in B but with wavelet phase lock analysis [smooth phase lock value (S-PLV)]. The regions with significant coherence and in phase lock between EMG and SBP in the time-frequency plots (B and C) are red and highlighted with bold black contours. The cone of influence (COI) is shown as a lighter shade. Each Venn diagram (B, top, and C, bottom) is composed of 3 ellipses, each of which represents the number of interactions between a pair of signals [i.e., EMG↔COPr, EMG↔SBP, and COPr↔SBP]. The overlapped regions signify that 2 or more pairs of signals are simultaneously coupled.
representative participant. The Venn diagrams in both LF and VLF were computed from one representation of muscle pump activation, were hypothesized to represent baroreflex-mediated muscle contraction (EMG and SBP) were found to make <10% of all observed interactions [%SC: 4.1 ± 0.8% (LF), 3.9 ± 1.9% (VLF); %PL: 5.5 ± 0.8% (LF), 6.2 ± 1.8% (VLF)]. The majority of the EMG interactions were with COPr only [%SC: 25.1% out of 37.0% (LF), 32.0% out of 42.5% (VLF); %PL: 18.1% out of 29.0% (LF), 20.4% out of 32.4% (VLF)]. When combined, the regions where SBP coupled with either COPr or EMG represent almost half of the total interactions [%SC: 19.3 ± 2.8% of 44.3% total (LF), 15.8 ± 3.4% of 47.9% total (VLF); %PL: 18.1 ± 1.8% of 36.3 total (LF), 18.3 ± 2.7% of 38.7 total (VLF)].

Areas where pairs of signals were simultaneously coherent and in phase lock were computed to EMG*SBP (LF: 2.7 ± 0.7%, VLF: 1.9 ± 0.7%), COPr*SBP (LF: 4.5 ± 1.2%, VLF: 3.8 ± 1.6%), and EMG*COPr (LF: 15.1 ± 3.3%, VLF: 17.5 ± 3.6%). From Table 1, we can observe that relative percent contributions of the three interactions display similar behavior regardless of whether coherence or phase lock is used. The unimodal pairwise interactions share the largest time percentage, the bimodal (2 pairs together) are substantially lower, and the trimodal interactions (3 pairs together) are higher than the bimodal interactions but substantially lower than the unimodal interactions (Table 1).

Mean significant coherence and S-PLV values ranged from 0.42 to 0.88 (Table 2). For all paired signals, these values were higher in the LF band. The highest mean values for both coherence and S-PLV in both frequency bands occurred with EMG*+COPr.

**DISCUSSION**

Our analysis has revealed evidence of an interdependent behavior between the cardiovascular and postural systems. The present work is the first attempt to systematically investigate and characterize the interdependent behavior of the posture and cardiovascular control systems under postural and orthostatic challenge. This link was hypothesized to exist via the activation of the skeletal muscle pump as a physiological response to cardiovascular perturbations and vice versa. To obtain evidence in support of the hypothesis, we conducted a passive sit-to-stand test with data collected from the cardiovascular (SBP), posture (COPr), and muscular (EMG) systems. A wavelet transform method, suitable for analysis of nonstationary signals, was applied to obtain the time-frequency representation of the signals. The significant coherence and S-PLV values were computed for each frequency band.

### Table 2. Averaged values of significant coherence and S-PLV measure for the three paired interactions in the two frequency bands

<table>
<thead>
<tr>
<th>Interaction</th>
<th>LF</th>
<th>VLF</th>
<th>S-PLV</th>
<th>LF</th>
<th>VLF</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMG*+COPr</td>
<td>0.74 ± 0.01</td>
<td>0.71 ± 0.03</td>
<td>0.88 ± 0.004</td>
<td>0.79 ± 0.05</td>
<td></td>
</tr>
<tr>
<td>EMG*SBP</td>
<td>0.67 ± 0.03</td>
<td>0.42 ± 0.06</td>
<td>0.87 ± 0.004</td>
<td>0.65 ± 0.07</td>
<td></td>
</tr>
<tr>
<td>COPr*SBP</td>
<td>0.68 ± 0.03</td>
<td>0.55 ± 0.05</td>
<td>0.88 ± 0.005</td>
<td>0.68 ± 0.07</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SE, averaged over 28 participants.
CARDIOPOSTURAL INTERACTIONS UNDER ORTHOSTATIC STRESS

A rapid rise in blood pressure (BP) is common during the initial 5 min of standing, but it is not immediately evident why. Our study aimed to investigate cardiopostural interactions in healthy aging and to understand how muscle activation mediates BP and postural sway.

We hypothesized that muscle activation would affect BP through postural control, as evidenced by muscle electromyography (EMG) and the center of pressure (COPr). The data from this study support our hypothesis and suggest that muscle activation can modulate BP by adjusting COPr, which in turn affects postural sway.

In conclusion, our study provides evidence for the importance of understanding the interplay between cardiovascular and postural systems in healthy aging. This is crucial for preventing orthostatic intolerance and related health issues.
Rapid Report

H264 CARDIOPOSTURAL INTERACTIONS UNDER ORTHOSTATIC STRESS