Stationary regime for Standing Wave Central Pattern Generator

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***Abstract*—The purpose of this research is to show that the spatio-temporal analysis on surface Electromyographic (sEMG) signals that originally confirmed existence of a standing wave Central Pattern Generator (CPG) along the spine are reproducible under less than ideal conditions and despite evolution of the entrainment technique, different hardware and data collection protocol. This analysis reveals a coherence at a distance between sEMG signals, which because of its large scale reproducibility could become a test for properly functioning Central Nervous System.**

***Index Terms*—Central Pattern Generator, standing wave, coherence, surface Electromyography**

I. Introduction

The so-called *spinal wave* [1] is a visually obvious phenomenon during which the spine goes through a rhythmic [2] oscillation elicited by light finger pressure at some sensitized areas of the spine, typically, the neck and the sacrum. As argued in our original work [3], Alf Breig's dural-vertebral attachments [4] have the effect of closing sensory-motor loops in both the neck and the sacrum, creating localized oscillations, which soon propagate along the spine to settle in a standing wave pattern. The crucial features that the movement is rhythmic, that it becomes self-sustained after some stimulus, hence has no sensory input, already point to a Central Pattern Generator (CPG), a concept that started with the movement of the lamprey [5, 6, 7, 8, 9] and that is still an active area of research [10]. Moreover, as reported in the earlier paper [3], a quadriplegic subject with a C2-C3 injury was able to experience some spinal wave pattern, which indicates that the CPG circuitry is embedded in the spine. It therefore appears that this movement is, next to gait, another human CPG.

A standing wave oscillation is certainly a manifestation of *coherence* in the neuro-skeletal system. Since the spinal standing wave has its coherence extending from the neck to the sacrum, it is fair to say that this is a phenomenon of *coherence at a distance* [3]. Coherence at a distance between EEG and/or (s)EMG signals is an indication of the nervous system able to coordinate activities of many muscles [11, 12]. The evidence that we presented in support of this paradigm is the deterioration of coherence in a quadriplegic subject compared with a control subject [3].

Nearly 10 years separate the data collection upon which [3] is based from the present one. During that time, the entrainment technique evolved to make the movement better controllable (the sEMG signals can be made smooth or bursty at will), the electrode positioning underwent some slight changes while we experienced with different orientation of the differential amplifier input prongs relative to muscle fibers, and the hardware (front-end electronics together with sEMG amplifiers) was upgraded. The software underwent some upgrade as well. Despite these changes and a 10-year span between the two experiments,

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we show that the early results [3] upon which the CPG hypothesis rests are reproducible, opening the road for the potential of this coherence analysis to become part of the suite of neurological assessment tests.

II. Methods

The control subject is a healthy individual who, prior to recordings, had signed the informed consent form approved by the Institutional Review Board (IRB) of the University of Southern California.

Four sEMG reduced-noise tripolar electrodes were placed at cervical (C2-C3), thoracic (T4-T6), lumbar (L3), and sacral (S2-S4) positions. The sensitive input prongs of the front-end electronics were aligned with the back muscle fibers [13]. The sEMG signals were amplified by an Insight Subluxation Station, Discovery model. The analog-to-digital conversion was done by a USB-1608FS card manufactured by Measurement Computing™ and running on a Windows XP platform.

A total of 720,000 samples were recorded at a rate of 4 kHz as shown in Figure 1. The analysis was centred around a section of 100,000 samples shown in Figure 2, where a phenomenon of synchronicity of signals is visually evident between 340,000 and 350,000 samples of raw sEMG data.

To highlight the differences between the protocol of the earlier study [3] and the one of the present study, we observe, first, that the sensitive prongs of the electrode front-end electronics were put at a 45 deg. angle relative to spine in the earlier study, as opposed to aligned with the fibers here. Second, the sacral electrode was positioned on the gluteus, as opposed to the sacrum as reported here. Third, the sEMG signals were amplified by an older Insight Millennium sEMG machine and the analog-to-digital conversion was done with a PC-Card DAS16/16, manufactured by Computer Boards (now Measurement Computing™), running on a Windows 98 operating system, as opposed to the upgraded equipment utilized here.

Let $y_1(k)$, $y_2(k)$, $y_3(k)$, $y_4(k)$ be the D_8 subband of the DB3 Daubechies wavelet decomposition of the cervical, thoracic, lumbar, and sacral sEMG signals, resp. The Daubechies DB3 is justified by its mother function that mimics the single Motor Unit Action Potential (MUAP) [14]. As in [3], we define the correlations

$$r_{ij}(s) = \frac{\sum_{k=1}^{K-s} (y_i(k) - \bar{y}_i)(y_j(k+s) - \bar{y}_j)}{\sqrt{\sum_{k=1}^{K-s} (y_i(k) - \bar{y}_i)^2} \sqrt{\sum_{k=1}^{K-s} (y_j(k) - \bar{y}_j)^2}},$$

where $\bar{y}_i$ is the sample mean of $y_i(k)$. As argued in [3], the movement has a coherent standing wave if there exist some delays $s_1 < s_2 < \ldots$ such that

$$r_{ij}(s_\ell) = 0; \qquad i, j = 1, 2, 3, 4; \qquad \ell = 1, 2, \ldots$$

The points s_ℓ, $\ell = 1, 2, \ldots$, have been called *zero correlation nodes* and are manifestations of a coherent standing wave. In [3], the research subject and the data segment were chosen so as to exhibit the zero correlation nodes in a strickingly obvious manner. Under more general circumstances, however, one cannot expect a perfectly coherent standing wave and the above will not, in general, hold for all ℓ's. In practice, one can expect the above to hold reasonably accurately for $\ell = 1$; the accuracy already deteriorates for $\ell = 2$; and in general not much can be expected for $\ell > 2$.

III. Results

The raw sEMG signals from the 4 electrodes are shown in Figure 1.

Eyeball inspection of the sEMG traces of Figure 1 already shows some coherence as there is evidence that the signals are bursting synchronously. For example, it suffices to look at the simultaneous bursting of all 4 signals around 700,000 samples to see some coherence.

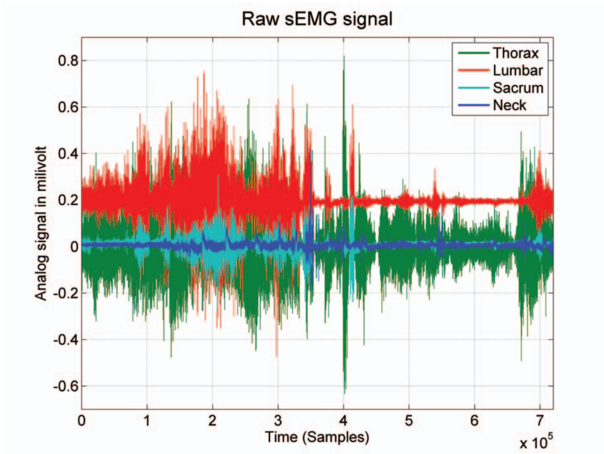


Fig. 1: Raw sEMG data at Neck, Thorax, Lumbar spine and Sacrum

However, for the sake of the coherence analysis, we focus our attention on the segment between samples 270,000 and 370,000. This section of raw sEMG is plotted in Figure 2.

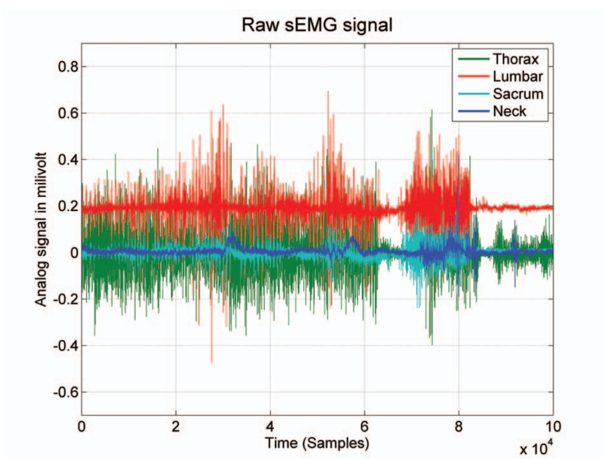


Fig. 2: Section from sample 270,000 to 370,000 of raw sEMG data at Neck, Thorax, Lumbar spine and Sacrum

Again, some synchronous bursting is visually obvious from Figure 2. Note that this bursty signal does not look quite like the one of Figure 1 of [3], which is much smoother. Nevertheless, the coherence results *remain qualitatively the same*.

A snapshot of the D_8 subbands of the Daubechies DB3 wavelet decompositions [15] of the 4 signals is shown in Figure 3. Most importantly, observe—consistently with Figure 2 of [3]—the synchronization doublet [16] of the sacral signal (marked with a circle and identified with a diamond $\diamondsuit$).

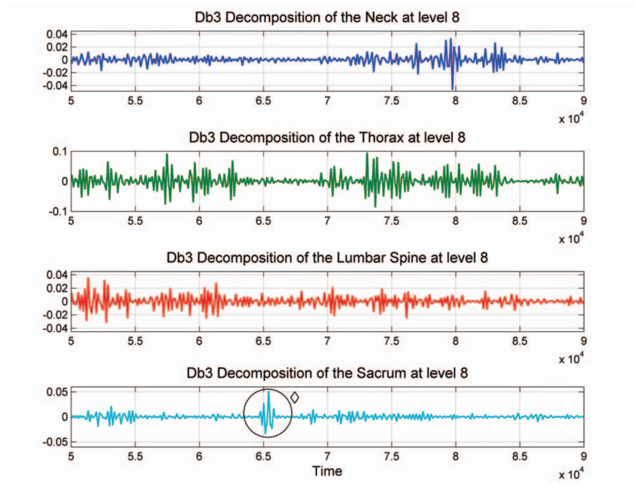


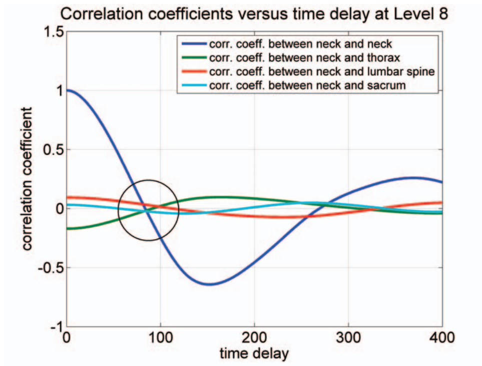
Fig. 3: D_8 subbands of Daubechies DB3 wavelet decomposition of Neck, Thorax, Lumbar spine and Sacrum signals, respectively

The cross-correlation between the 4 different sEMG signals obtained from subband D_8 is shown in Figure 4.

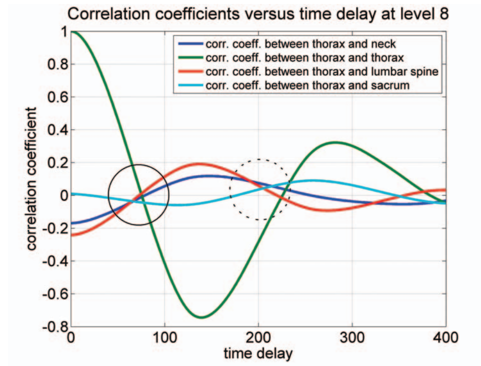
The plots from Figures 4a-4d are quite similar to those of the left panels of Figures 3-6 of [3]. The s_1 zero correlation nodes (marked with black circles) develop with the same level of accuracy as in [3], while the s_2 nodes (marked with dotted circles) can be seen, but not as markedly as the s_1 node, exactly as in [3].

IV. Discussion

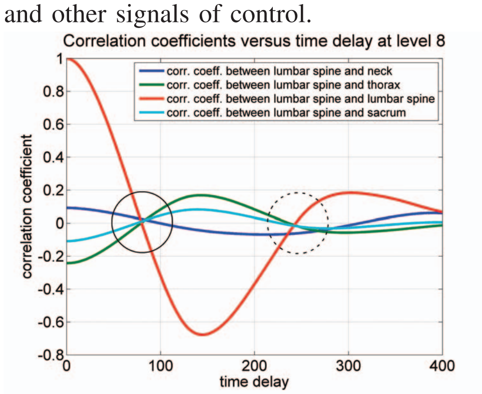
Observe in Figure 4 the well-defined "zero correlation nodes," i.e., the common points of intersection of all the $r_{ij}(s)$ versus s curves and the $r = 0$ axis, strong evidence of a coherent standing wave. Both the s_1 nodes and to a less extent the s_2 nodes are visible (marked with solid and dotted circles, resp.). Also note the consistency between the synchronization doublet of Figure 3, sacrum, and the s_1 node of Figure 4, sacrum (d), both of them identified with a diamond $\diamondsuit$. As such, it is fair to say that the results of [3] have been reproduced in an environment deliberately taken not as "selective" as that of [3].



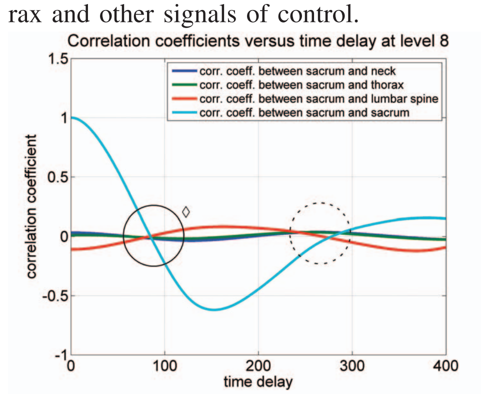
(a) Correlation between D_8 subbands of neck and other signals of control.



(b) Correlation between D_8 subbands of thorax and other signals of control.



(c) Correlation between D_8 subbands of lumbar and other signals of control.



(d) Correlation between D_8 subbands of sacrum and other signals of control.

Fig. 4: Correlation on D_8 subband among the 4 signals from sample 270,000 to 370,000

V. Conclusion

We demonstrated the reproducibility of the results of [3] indicating that the spinal wave is a coherent movement elicited by a Central Pattern Generator. Here *reproducibility* spans across a period of 10 years, during which many changes in the protocol, the experimental hardware, the software, etc. occurred, hence demonstrating the "robustness" of the early results. As evidence that degradation of coherence is a sign of a neurological deficit, it was shown in [3] that a quadriplegic subject does not exhibit as clear zero correlation nodes as a control subject. Development of a statistical test to determine with sufficient confidence when coherence is depleted to a level that should call for neurological follow up is of a difficult mathematical challenge.

A hypothesis testing for time-domain coherence at D_8 remains to be developed. In the frequency-domain, coherence can be assessed by significance of the cross power spectral density at some coherent frequency. In [17], we established with 95% confidence that the coherent frequency is multiplied by a factor of 2 along the entrainment, meaning that coherence transits from the D_8 to the D_7 subband, consistently with a faster movement, with more antinodes in the waveform.

All of the above applies to a spinal wave characterized by two mode shape antinodes, a wave that normal subjects are able to develop with minimum entrainment. A more complicated wave with three mode shape antinodes can be elicited, but with more difficulties though. From elementary wave physics, this more complicated wave should exhibit some coherence, but this remains to be demonstrated in the realm of clinical data.

In summary, the present and the related studies make a case that sEMG coherence has the potential to lead to new neurological tests.

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