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Research Article

Sway Spectral Analysis in the Instrumented Romberg Test: Is there a Correlation between the Most Evident Harmonics of Closed Eyes Sway and Musculoskeletal Dysfunction Foci? A Medical Hypothesis Based on Clinical Experience

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Abstract

It is generally accepted that musculoskeletal pain can affect balance control, and the instrumented Romberg test performed on a static force plate allows practitioners to assess this aspect of functional performance. During our routine clinical practice, we used a metrologically validated force plate with a high degree of precision (error less than 0.1 mm) to measure center-of-pressure (COP) coordinates throughout a 10 Hz bandwidth. Comparing these results with a normal sample we noticed that the spectral composition of the latero-lateral and antero-posterior sway correlated to the painful condition reported by the patient, or to an unresolved “functional compensation”. Based on the inverted pendulum model, we suggest that the frequency of un-dampened harmonics – mainly during closed eyes recordings – correlates with the height of the disturbing focus (0.9 Hz for the ankles to 0.1 Hz for the head). Six examples show the effects on the harmonic analysis of a variety of conditions. A device capable of providing this type of information may prove to be extremely useful in a clinical setting for understanding the patient’s condition, planning an appropriate rehabilitation program, and monitoring the outcome of treatment.

Keywords: Romberg Test; Force Plate; Harmonic Analysis; Nociceptive interference

Introduction

The Romberg test, a classic neurology test to assess proprioceptive deficits, was proposed in 1836 by Professor Moritz Heinrich Romberg and consists of the patient keeping an unperturbed upright stance, while the neurologist compares the amount of sway with the patient's eyes closed to that with the patient's eyes open. Romberg's ingenious solution for measuring sway was to attach a feather to the patient's head in a vertical position, and to measure the trajectory traced by the feather on a soot-covered wooden plate suspended over the patient's head [1]. This operation is much easier nowadays [2]: a force plate gives the coordinates of the center of pressure (COP) on its surface, by way of simple calculation [3]. The COP under the soles of the foot is defined as the point of location of the vertical ground reaction force vector - the sum of all pressures exerted on the surface of the plate through the foot soles for the purpose of keeping balance while standing upright. Sampling the recording several times per second the COP path appears rather smooth, and a growing number of parameters measurable from its coordinates have been proposed to permit and support diagnostic assessment [4].

In addition to the well-known parameters to describe trajectory (sway path, sway area, standard deviation of the oscillations) or express the distribution of the COP positions sampled during the test (the smallest ellipse containing the mean COP and 95% of the sampled points), other "structural" parameters have been proposed to show the "structure" of the sway which results from a combination of anticipatory commands and low frequency feedback controls [5].

An important contribution to the analysis of balance control has come from the harmonic analysis of both frontal and sagittal plane sway [6]. The idea comes from the Fourier theory, which allows the time variation of the coordinates of a stationary oscillatory movement to be transformed into the sum of elementary sinusoidal oscillations with a specific amplitude, frequency, and phase. Without going into the details of the mathematical process [7], it is worth noting that the presence of "harmonics" – the name given to the individual sinusoidal oscillations – suggests a repeatable phenomenon responsible for those specific oscillations, and that the intensity of those oscillations is directly proportional to their amplitude.

Balance while standing is intrinsically unstable: the center of mass is slightly under the umbilicus (about 55% of subject height from the ground), placing it well above the ankle axis. The system of balance control in humans solves the biomechanical problem of keeping the body in an intrinsically unstable position by modulating the pressure exerted on the ground through the soles of the feet. This system must also control the many body segments which pivot around the joints and hinges connecting the skeleton.

To maintain a so-called "stable" upright stance, humans need to correct any oscillations via a combination of proprioceptive input and the motor control patterns adaptively learned and continuously updated based on the body's anthropometrics. The study of human balance control mechanisms has received a tremendous boost from the studies performed to design bipedal humanoid robots capable of walking and standing while performing different tasks. The combination of actuators across the joints (agonists and antagonist as muscles) was immediately adopted by researchers, together with overall control mechanisms involving feed-forward [8] and feedback functions [9].

By observing the structure of the human skeleton and the distribution of skeletal muscles, researchers recognized that a good model for understanding the behaviour of balance keeping was the inverted pendulum [10, 11], and a multi-segmented one at that, where segments are interconnected by the specific joints. More recently, however, the single segment pendulum has been suggested as a better option [12]. The oscillations of a pendulum depend solely on its length: the longer the pendulum arm, the lower its frequency of oscillation (Figure 1). The mathematics of the pendulum is shown in (Table 1).

Figure 1: A Metronome: an inverted pendulum whose arm length can be adjusted to providethe required oscillation frequency

The natural frequency of a pendulum (small oscillations)		
$$f = \frac{1}{T} = \frac{1}{2\pi\sqrt{\frac{l}{g}}}$$		
Symbol	**Meaning**	**Unit**
f	Frequency	Hz
T	Period of oscillation	seconds
$\boldsymbol{\pi}$	Numeric constant (3.141593)	
l	Pendulum length (in humans 0.55 x the subject height [m], therefore ranging from 0.9 for a height of 160 cm, to 1.1 for a height of 200 cm)	m
g	Gravity (9.81 m/sec2)	m/sec2
Applying the formula, the natural frequency of the oscillation of a standing human modeled as asingle inverted pendulum ranges from 0.52 Hz for a height of 160 cm to 0.47 Hz for a height of 200 cm.		

Table 1: Frequency of an oscillating pendulum.

From our experience the differences of harmonics' frequencies due to the subject stature seem much smaller than the ones coming from the sole mathematics. We suppose that the viscoelastic properties of muscles and joints account for a much smaller variability, and we propose to use a normalized stature to the mean values reported, for example, by NASA for the 50th percentile of the American Males/Females (Figure 2).

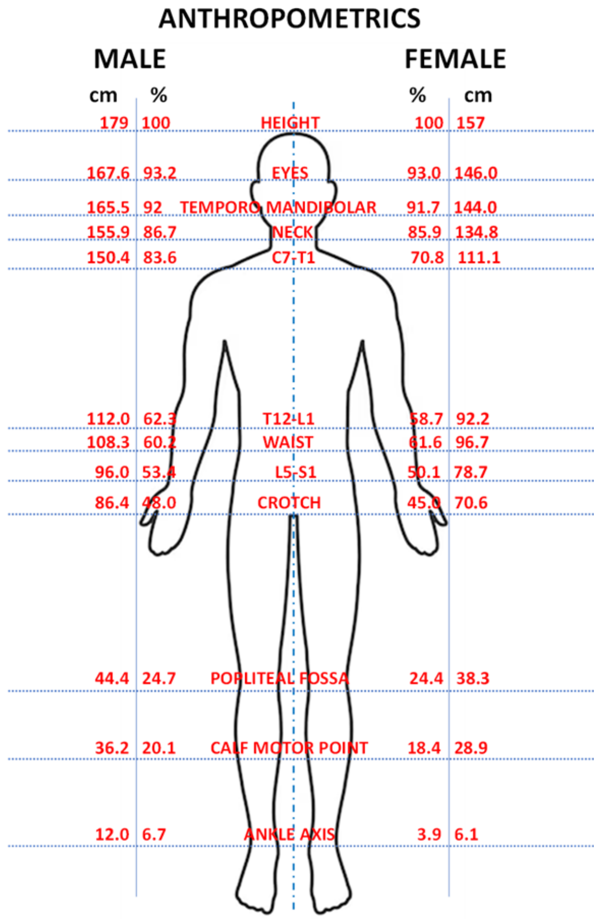

Figure 2: Normalized height (US 50th percentile population) (From NASA document retrieved on April 10, 2023 @ https://msis.jsc.nasa.gov/sections/section03.htm)

Previous observations, presented in deeper detail in the next paragraph – see, for example [13], – have shown the sway of standing humans to occur at frequencies under 1 Hz.

It has been demonstrated that although the classic free oscillating pendulum depends exclusively on the height of the center of mass, the human pendulum-like model should be adjusted to consider the viscoelastic properties of the antagonist muscles [14, 15] which stabilize all the joints responsible for the multisegmented pendulum-like behavior of the human body.

At the end of the design phase of the balance force plate (ArgoPlusMK1 by Fremslife Genoa, Italy), a sample of normal subjects was tested to give the reference values for all parameters. Testing involved the subjects standing in an upright position with feet together, with closed and open eyes, for a recording time of 40 seconds and a sampling rate of 100 Hz, and the normal ranges (mean ± 2 std. dev.) were calculated for all parameters, including the harmonic spectral power, in 16 sub-bands, 8 on the frontal and 8 on the sagittal plane. The sample consisted of 195 healthy young volunteers, 119 of whom were elite athletes [16] and was subsequently extended to a total of 1212 normofunctional individuals. Since then we have collected several thousand test results during our routine clinical practice, investigations which included a specific test to explore the feasibility of using the Romberg test as a screening tool for balance deficits [17], and we noticed the as-yet unreported relationship between the harmonic analysis and the position of what could perhaps be described as an irritative focus. It was only during a recent discussion of the topic that the co-authors of this paper came to exchange experiences and comments which led to the definition of the present medical hypothesis.

The typical distribution of the harmonic spectral power over 8 bands was calculated from the observed characteristics of the sample of 1212 normofunctional individuals (Table 2 and Figures 2 and 3). While developing the normal parameters from this population, the normal harmonic spectrum values were also extrapolated.

	Females (610)				Males (602)			
	Height(cm)	**Weight(kg)**	**EU footsize**	**BMI**	**Height(cm)**	**Weight(kg)**	**EU footsize**	**BMI**
Mean	157.22	48.08	37.70	18.68	162.48	54.26	40.32	20.55
Std Dev	55.06	13.40	2.83		21.88	19.02	4.95	
Median	158	51	38		168	53	41	

Table 2: The sample.

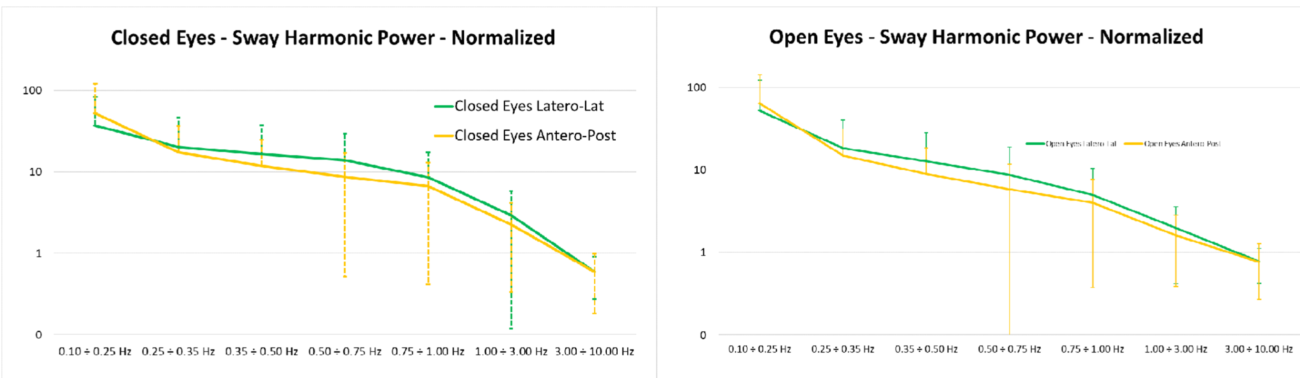

Figure 3: The normalized sway harmonic power in norm functional individuals.

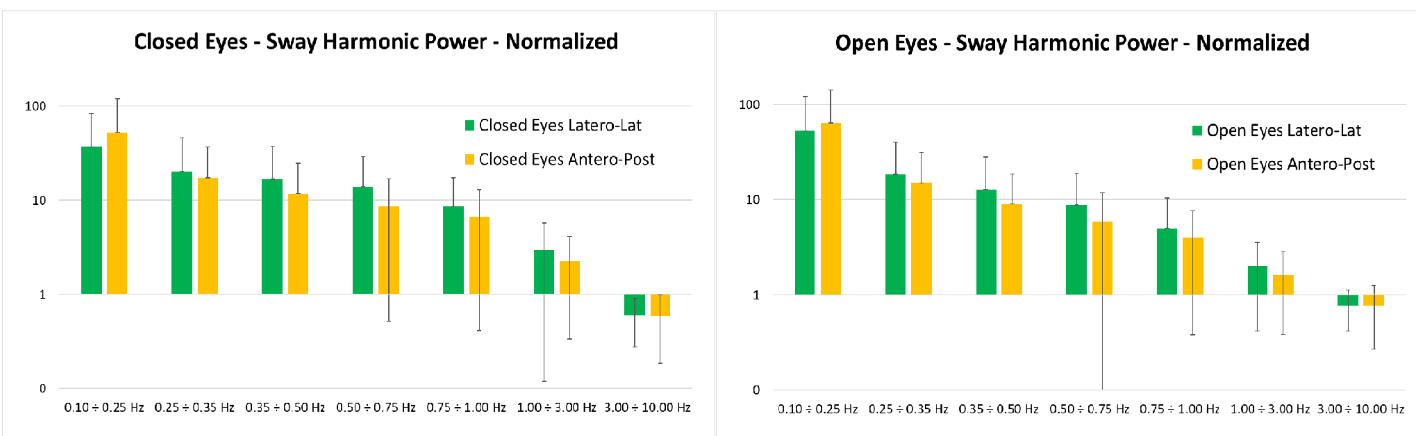

Figure 4: The absolute sway harmonic power values in normofunctional individuals.

The selected bands (Table 3 and Figure 5) were defined based on the hypothesis of a possible correlation to body segments, according to the inverted pendulum logic.

BAND	POSSIBLE CORRELATION	Latero-Lat. limit(mm^2/Hz)		Antero-Post. limit(mm2/Hz)	
		ClosedEyes	OpenEyes	ClosedEyes	OpenEyes
0.00 to 0.10 Hz	Head, eyes, vestibulum, stomatognathic interferences	(*)	(*)	(*)	(*)
0.10 to 0.25 Hz	Neck, shoulders	256.63	249.68	358.02	314.43
0.25 to 0.35 Hz	Chest, upper limbs	140.67	87.66	118.39	73.62
0.35 to 0.50 Hz	Lumbosacral region	115.28	60.88	80.24	44.23
0.50 to 0.75 Hz	Hips, knees	96.90	41.75	59.20	28.89
0.75 to 1.00 Hz	Ankles, feet	59.61	23.67	45.56	19.79
1.00 to 3.00 Hz	Tremors, jerks and other neurological signs	20.36	9.46	15.24	7.91
3.00 to 10.00 Hz		4.11	3.68	4.01	3.78
0.00 to 10.00 Hz	Total bands	693.55	476.79	680.66	492.65
(*) The normative values for the first sub-bands were not calculated because of the insufficient recording time span in the standardized test (40 sec)					

Table 3: Sub-band distribution of the total calculated total harmonic power (mm^2/Hz).

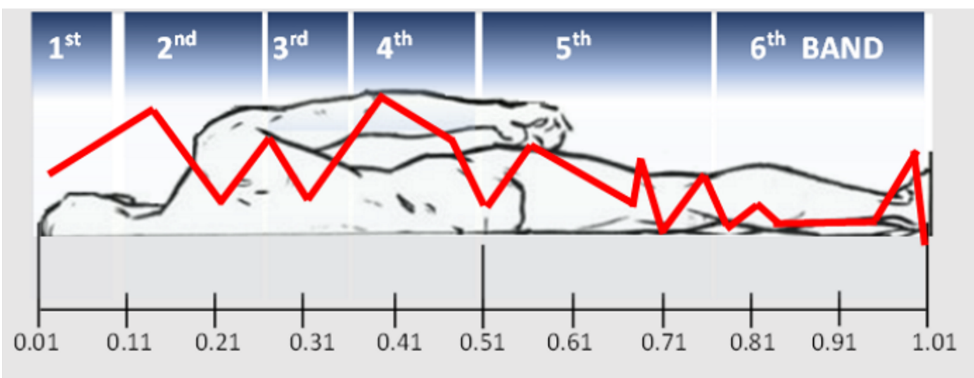

Figure 5: Correspondence between skeletal segments, frequencies, and spectral bands.

A large body of literature – for example [18–29] –claims that postural sway is modified by musculoskeletal pain, although we have also found a paper demonstrating that the most widely used balance parameters (mean sway velocity and sway area) are not affected by such pain [30].We believe that force plate parameters are not always reliable, therefore it is crucial to select those which are most appropriate [31]. We also believe that harmonic analysis can constitute a reliable tool for detecting the presence and position of a focusresponsible for generating nociceptive interferences – even those under the pain perception threshold.

The assumption of the authors presented in this manuscript is that the frequency of a peak in the harmonic analysis of the recording performed with closed eyes is closely correlated to the position of the irritative focus which causes that specific sway anomaly. It is worth noting that such a focus may be accompanied by pain or be a residual compensation of an old injury requiring rehabilitation or re-education. This hypothesis, however, should be further explored to provide a more specific and reliable correlation.Several technical/ operational requirements must be met to permit an analysis of the oscillation harmonics from the sequence of COP positions:

a) To calculate the COP coordinates, the signals from the load cells should be sampled and filtered (a second order Butterworth filter with a 10 Hz cut-off frequency is recommended) to provide reliable information.

b) The filtered COP coordinate output must be at a frequency higher than the one expected in the oscillation by at least one order of magnitude [32]. Its resolution depends on this frequency: the higher the better.

c) The recording time should be as long as possible (the lowest detectable frequency is inversely proportional to the acquisition interval) as a compromise between the achievement of a steady state and the onset of fatigue in dysfunctional subjects, or attention loss in healthy subjects who find the task easy to complete [33].

d) Testing should be done under normal environmental conditions [34].

e) The subject should assume a normal standing position on the force plate [35].

Materials and Methods

Measurements were performed using the Force Plate ArgoPlusMK1 (Fremslife – Genova Italy). The main characteristics of the device are given in (Table 4).

FORCE PLATE MAIN CHARACTERISTICS	
Platform size	600 x 600 mm – 12 Kg
Natural Frequency	> 300 Hz
Patient's weight range	15 – 200 Kg
Type of sensors	Strain gauges
Output	COP Position (x, y) vs. time
COP accuracy	<0.1 mm Band 0 – 10 Hz
Sampling rate	100 Hz
Data Processing	The COP path is low pass filtered (Butterworth 2nd order) with a 12.5 Hz cut-off filter
Main output parameters	Sway Path, Sway Area Sway Oscillations (x, y) 95% Confidence Ellipse, HarmonicAnalysis, Sway Density, Score Of Postural Functionality, Limits-Of-Stability
Display	Stabilogram, Statokinesiogram, Sway Spectrum
TEST MODE	
Platform position	Patient head at abt 1 m from the wall devoid of any marking except a black dot (Ø 30mm) at the height of the eyes
Recording	40 sec (plus 5 seconds for task adaptation) each phase
Test Sequence	2 phases: Closed Eyes and Open Eyes
Feet position	Barefoot Joined parallel
Arms	Freely hanging at sides
Head	Up - horizontal view
Mouth	Closed unclenched teeth
Sight	Straight frontal (Open eyes)

Table 4: ArgoPlusMK1 Characteristics.

The Sway Harmonic analysis was calculated from the recorded stabilogram values (X, Y coordinates vs. time) using the Non-Parametric Welch FFT algorithm [36].From the 4,000 recorded values (40 seconds at 100 Hz) the FFT provides 300 values at 0.012207 Hz interval having excluded the values under 0.1 Hz as non-significant.

The spectrum graph is therefore given with 300 values on the logarithmic scale to give a good visual resolution in the frequency range up to 1 Hz. Dataset were selected among the ones recorded on subjects occasionally visiting the Physiotherapy wards for musculoskeletal rehabilitation. Patients gave their written consent to the anonymous publication of the evidence collected. Full data set may be made available on request.

Results

The following examples are being reported to support the hypothesis of a correlation among the harmonics' frequencies and their originating focuses.

Application example 1 – Treatment of a musculoskeletal condition

Spectral analysis of the instrumented Romberg test performed on a 79-year-old female patient (155 cm tall, weighing 70 Kg) who had undergone total right hip arthroplasty and was complaining of persistent hip pain while standing (Figure 6).

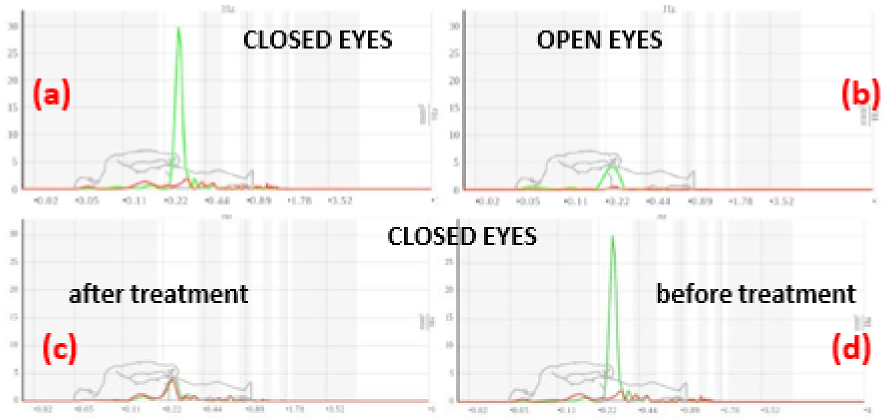

Figure 6: Spectral analysis of the instrumented Romberg test performed on a 79-year-old female patient. Green plot = latero-lateral sway; red plot = antero-posterior sway. Horizontal axis shows frequencies, whilevertical axis shows harmonic power (mm²/Hz). Note that graphs (a) and (d) are identical (harmonic power vs frequency in the closed eyes recording prior to treatment)

Gait functionality was impaired. Harmonic analysis indicated the likelihood of a proprioceptive interference, as demonstrated by the difference between graphs (a) (closed eyes recording) and (b) (open eyes recording) caused by nociceptive stimuli and demonstrated the effect of a rehabilitative treatment: graphs (d) and (c) show the closed eyes recordings before and approximately 45 minutes after an effective rehabilitation treatment (laser acupuncture with Libralux by Fremslife (Genoa – Italy)).

Application example 2 – Treatment of a central deficit

The high frequency harmonics of neurological interest can also be seen, and a differential "ex-adjuvantibus" diagnosis can be made to support the treatment program (Figure 7).

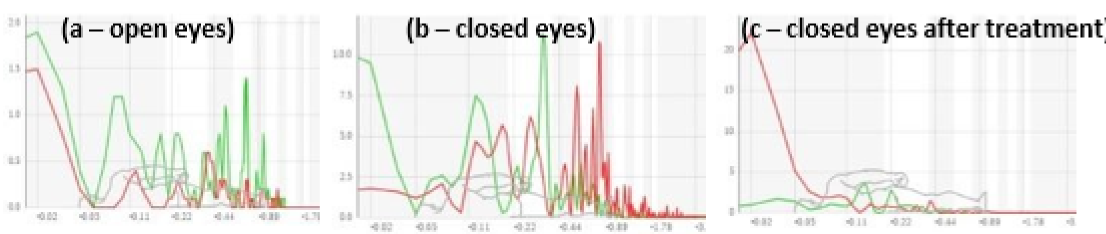

Figure 7: Harmonic plot of a patient following a traumatic event with suspicion of cerebellar injury.

Although his vision compensated the closed eyes sway [please see (b) vs. (a) graphs –note that in (b) the verticalaxis has top values over 100 mm²/Hz, while in (a) they are under 20] the graphs showed a significant dysfunction. Besides the high frequency harmonics that are strongly suggesting a cerebellar involvement, the harmonics at 0.1 Hz are consistent with a latero-lateral cervical condition (cervicothoracic hinge) with a latero-lateral harmonic at coccygeal level (0.35 Hz) which may be compensatory. These harmonics are still visible following treatment, albeit at a reduced level (2.5÷3 mm²/Hz instead of 7.5÷11).

The patient was tested again 25 minutes after treatment (closed eyes only), significantly reducing the high frequency harmonics [(c) vs. (b) graphs] to almost normal levels. The antero-posterior harmonics at 0.07, 0.11,0.15 and 0.25 Hz disappeared.

A patient was examined following a traumatic event with suspicion of a cerebellar injury, undergoing Romberg testing on the ArgoPlusMK1 device. Although his vision appeared well compensated, the closed eyes sway was consistent with significant dysfunction. Although the likelihood was of a centrally originated dysfunction, the patient was undergoing rehabilitation treatment at the time (laser acupuncture with Libralux by Fremslife (Genoa – Italy)). The patient was tested again 25 minutes after treatment (closed eyes only), showing that the laser acupuncture treatment had significantly abated the high frequency harmonics to an almost normal level. Unfortunately the patient's symptoms returned three days after treatment, confirming the need for further neurological investigations. It is to remark that the major harmonics at frequencies under 0.05 Hz are non-significant because the minimum detectable frequency is reciprocal to the recording time (40 sec and, therefore, 1/40 = 0.025 Hz).

Application example 3 – Compensation of an old injury

Harmonic analysis is also able to show the presence of interference due to an old, apparently compensated injury. While functionality in bending, walking, and performing life activities was not impaired, and the subject gave no medical history prior to the test, harmonic analysis (Figure 8) suggested the presence of a dysfunction.

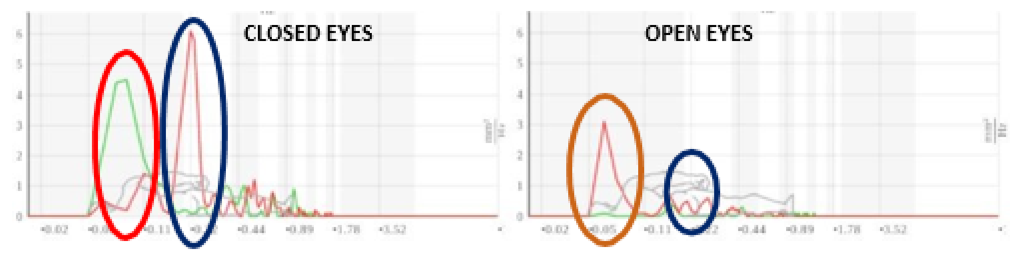

Figure 8: Harmonic plot of a patient after a traumatic event: functionality in bending, walking, and performing life activities was not impaired.

Harmonic analysis of the closed eyes recording shows an undampened antero-posterior harmonic (blue oval) pertaining to a sagittal compromise at the lumbar level, fully compensated by the patient's vision (small blue oval) at the cost of a cervical compensation (brown oval). The red oval in the closed eyes test shows a latero-lateral cervical oscillation corresponding to some "noise" in the region of the knee joint.

The harmonic analysis of the closed eyes recording showed an undampened antero-posterior harmonic (blue oval) pertaining to a sagittal compromission at the lumbar level, fully compensated by the patient's vision (small blue oval) at the cost of a cervical compensation (brown oval).

The red oval in the closed eye test showed a latero-lateral cervical oscillation corresponding to some "noise" in the region of the knee joint. Following specific questions on his medical history, the patient reported a motorbike accident (3 years previously) in which he suffered an injury to the lumbar spine, treated with 6 months' immobilization (corset) of the lumbosacral spine. It could be concluded that the rehabilitation process did not restore full mobility of the spine.

Application example 4 – Acute orthopedic injury

A patient presented with a fracture to the humeral head due to a bicycle accident (Figure 9). The fracture was clearly shown by the harmonic analysis of the closed eyes recording. Note the compensation at the thoracolumbar hinge.

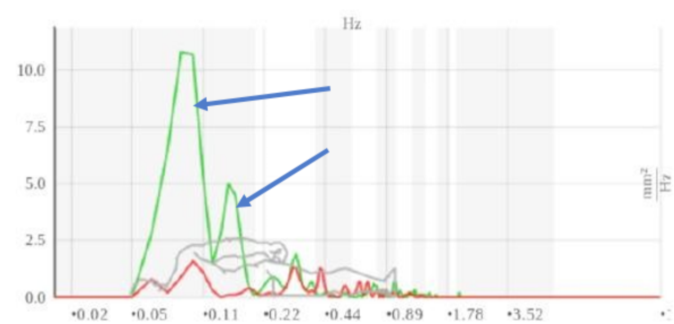

Figure 9: Orthopedic injury following a bicycle accident.

Application example 5 – Musculoskeletal pain interference

A 65-year-old cyclist was unable to practice more than 20 minutes due to unbearable monolateral hip joint pain. Harmonic analysis clearly showed interference well compensated by visual input (Figure 10), while the Romberg test showed visually compensated musculoskeletal interference. The frequency of the main harmonic (0.35 Hz) in the latero-lateral oscillation during the closed eyes recording suggested a monolateral lumbosacral origin (hip joint).

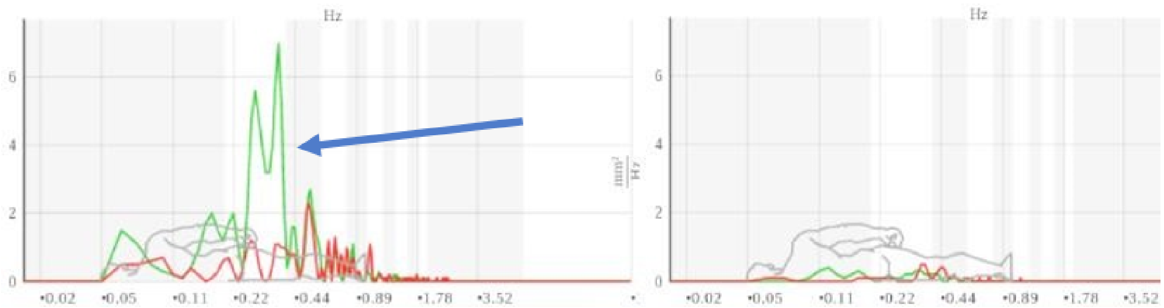

Figure 10: The Romberg test shows a visually compensated musculoskeletal interference. The frequency ofthe main harmonic (0.35 Hz) suggests a monolateral lumbosacral origin (hip joint).

Application example 6 – Postural instability

An 83-year-old woman complained of postural instability. The Romberg test suggested a possible patellofemoral syndrome and following physiotherapy treatment with a Vibra device (Vibra 3.0 by AD SWISS MEDTECH SA – CH), the patient reported a significant improvement, confirmed by a second measurement 15 days after physiotherapy treatment (Figure 11).

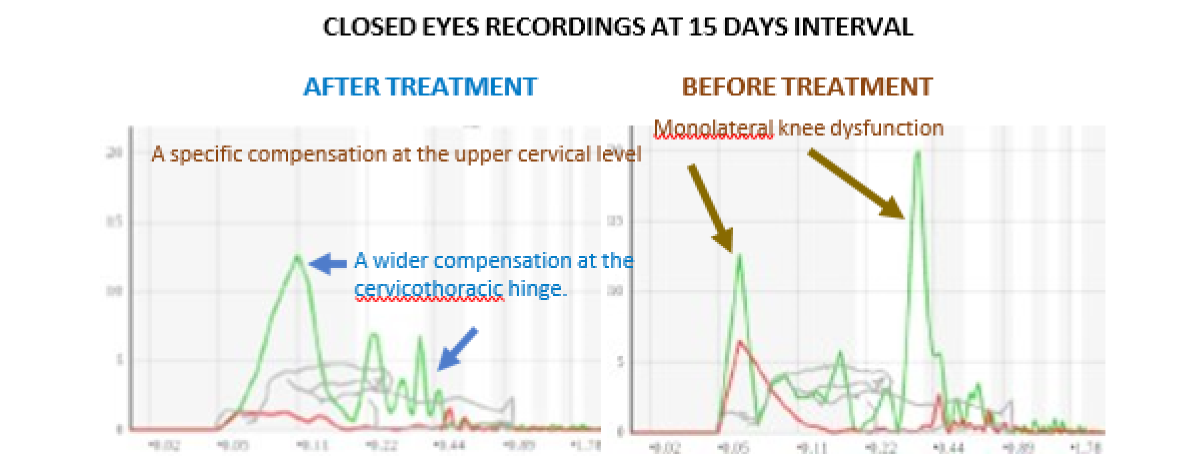

Figure 11: Reduction of latero-lateral postural stability, probably due to a monolateral patellofemoral syndrome, treated and measured before and after a rehabilitation program. The harmonic at 0.4 Hz was strongly reduced.

Discussion

Postural control requires maintenance of an unperturbed upright stance. This ability involves spinal and brain stem structures, as well as cortical areas which are fundamental for adjusting the motor commands from the peripheral receptors, such as the condition of the body and environmental changes [37]. Proprioceptive signals play an important role in postural control, due to the low proprioceptive threshold linked to body sway [38,39]. The muscle spindles play a key role in this context, conveying information about changes in muscle length and speed of contraction: indeed, lengthening of the muscle activates the receptors and the consequent transmission of the action potential through the afferent fibers and to the alpha motoneurons and interneurons, conveying the proprioceptive information to the sensorimotor cortex and to the cerebellum [40]. Both physiological and pathological conditions alter the proprioceptive system with a possible consequent increase in body sway, impaired balance, and a higher risk of falling [41]. In fact, the ability to detect and compensate for body sway by adjusting leg muscle length via rotation around the ankle joint is an important component of postural control [42].

Painful conditions may interfere with postural control, irrespective of the underlying pathology. Although the exact mechanisms are still unclear, one possible explanation may be the loss of proprioception consequent to a painful stimulus [43], indeed the activation of nociceptive fibers Aδ and C which convey the signal at a spinal level may lead to a reflex excitation of ϒ-motoneurons and to a consequent hypersensitivity of muscle spindles [44]. While this has only been demonstrated in animal models, with experimentally induced pain in humans not appearing to induce changes in muscle spindle activity [45,46], there is a probable link between pain and proprioceptive deficits in the central nervous system (CNS), in both the motor and somatosensory cortex [47,48].

A recent study by Carvalho and colleagues demonstrated impaired balance control in patients with headache [49]. Among the different possible explanations, the authors hypothesized a mismatch between the abnormal afferent inputs from the painful neck and the normal information from the vestibular and visual systems. A correlation between chronic Low Back Pain (LBP) and increased body sway in the upright static and dynamic standing positions has also been demonstrated [50]. Chronic pain appears to act on the temporal activation of paraspinal muscles, resulting in a delayed muscle response to the external perturbations, impaired segmental stability, and pain-mediated reduced muscle contraction, with a compensatory activation of non-primary muscles [51,52].

In our study we observed:

- Modification of the harmonic analysis spectrum following an effective musculoskeletal pain treatment: the latero-lateral harmonic related to the hip joint (frequency slightly short of 0.3 Hz) was reduced by more than 80% after treatment (example 1). The correspondence betweenfre quency and focus height was confirmed, and the latero-lateral sway (green line plot) confirmed the monolaterality of the focus.
- A striking difference in the harmonic analysis of the closed eyes recordings of a subject with a functional deficit of central origin before and after a laser acupuncture treatment aimed at giving temporary relief from the deficit and improve quality of life (example 2). It is worth noting that in addition to the high frequency “noise” of central origin, certain harmonics indicating a compensatory balancing of sway harmonics caused by musculo-skeletal interference were significantly reduced.
- Spectral evidence of an old uncompensated injury (example 3).
- Correlation of an orthopedic injury (fracture of the humerus) and the latero-lateral sway harmonic at the frequency corresponding to the shoulder girdle. The presence of a second evident harmonic at the frequency corresponding to the thoracic spinal tract probably suggests a compensatory activity by the spinal column (example 4).
- Three harmonics present in the closed eyes recording and clearly indicating unbalanced activities of three column hinges [cervicothoracic (0.10 Hz), lumbo-sacral (0.20 Hz) and coccygeal (0.35 Hz)] are being dampened while the subject stands with open eyes. The musculoskeletal pain interference originating from the hip joint, probably exacerbated due to prolonged periods spent in the racing position as a cyclist, is the most likely cause of the perceived hip pain (example 5).
- Postural instability due to a monolateral knee dysfunction (patellofemoral syndrome) emerged in the closed eyes position prior to treatment. A positive modification was observed during the rehabilitation program, resulting in a significant reduction of the knee-related harmonic.
- Interestingly, the effects on the column stabilization can be observed and will require specific treatment to restore the appropriate balance (example 6).

Conclusions

The selected examples show this approach to be extremely promising, although further studies are required to better understand the neurophysiological model supporting the results, and to provide statistically sound evidence from clusters of subjects under homogeneous clinical conditions. We believe, however, that even at this preliminary stage, harmonic analysis of static balance sway constitutes a valuable tool in the functional evaluation of individuals who consult rehabilitation clinics seeking treatment for musculoskeletal conditions, providing crucial insights into the appropriate rehabilitation program, and allowing practitioners to measure the effects of treatment.

Author Contributions

Conceptualization, Michele Gallamini; Investigation, Gianluca Bernabei, Nicolò Fortis, Giuseppe Celeste and Francesca Faso; Supervision, Lucrezia Tognolo; Writing – original draft, Michele Gallamini. The authors independently performed the measurements using the same device (ArgoPlusMK1 by Fremslife Genoa – Italy) and discussed the results with LT to develop the medical hypothesis of this paper. All authors have read and agreed to the published version of the manuscript.

Institutional Review Board Statement

The study was conducted according to the guidelines of the Declaration of Helsinki. Ethical review and approval were waived for this study where examined data were gathered during routine clinical activity. All the involved subjects gave their formal consent to the anonymous publication of the data pertaining to the performed tests.

Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Data Availability Statement

Data may be made available on request.

Conflicts of Interest

MG Is a minority shareholder (<1%) of Fremslife Srl producer of ArgoPlusMK1 Force Plate and took part to the development of the device. The other authors declare no conflict of interest.

References

1. Lanska DJ. (2002) The Romberg sign and early instruments for measuring postural sway. Semin Neurol.22:409-18.
2. Lanska DJ, Goetz CG. (2000) Romberg's sign: development, adoption, and adaptation in the 19th century. Neurology.55:1201-6.
3. Bobbert MF, Schamhardt HC. (1990) Accuracy of determining the point of force application with piezoelectric force plates. J Biomech.23:705-10.
4. Raymakers JA, Samson MM, Verhaar HJ. (2005) The assessment of body sway and the choice of the stability parameter(s). Gait Posture.21:48-58.
5. Jacono M, Casadio M, Morasso PG, Sanguineti V. (2004) The sway-density curve and the underlying postural stabilization process. Motor Control.8:292-311.
6. McClenaghan BA, Williams H, Dickerson J, Thombs L. (1994) Spectral signature of forces to discriminate perturbations in standing posture. Clin Biomech (Bristol, Avon).9:21-7.
7. https://en.wikipedia.org/wiki/Fourier_transform
8. Gatev P, Thomas S, Kepple T, Hallett M. (1999) Feedforward ankle strategy of balance during quiet stance in adults. J Physiol.514:915-28.
9. Tin C, Poon CS. (2005) Internal models in sensorimotor integration: perspectives from adaptive control theory. J Neural Eng.2:S147-63.
10. Pasma JH, Boonstra TA, van Kordelaar J, Spyropoulou VV, Schouten AC. (2017) A Sensitivity Analysis of an Inverted Pendulum Balance Control Model. Front Comput Neurosci.11:99.
11. Suzuki Y, Morimoto H, Kiyono K, Morasso P, Nomura T. (2015) Non-actively controlled double-inverted-pendulum-like dynamics can minimize center of mass acceleration during human quiet standing. Annu Int Conf IEEE Eng Med Biol Soc.1432-5.
12. Morasso P, Cherif A, Zenzeri J. (2019) Quiet standing: The Single Inverted Pendulum model is not so bad after all. PLoS One.14:e0213870.
13. Bensel CK, Dzendolet E. (1968) Power spectral density analysis of the standing sway of males." Perception & Psychophysics 4: 285-288.
14. Van Loocke M, Lyons CG, Simms CK. (2008) Viscoelastic properties of passive skeletal muscle in compression: stress-relaxation behavior and constitutive modelling. J Biomech.41:1555-66.
15. Simms CK. (2012) Passive skeletal muscle mechanical behaviour: considerations for constitutive modelling. Comput Methods Biomech Biomed Engin.15:271.
16. Gallamini M, Piastra G, Porzio D, Ronchi M, Scoppa F, et al. (2016) Instrumental Assessment of Balance Functional Performance. A Numerical Score to Discriminate Defective Subjects: A Retrospective Study. J Nov Physiother 6: 305.
17. Gallamini M, Piastra G, Lucarini S, Porzio D, Ronchi M, et al. (2021) Revisiting the Instrumented Romberg Test: Can Today's Technology Offer a Risk-of-Fall Screening Device for Senior Citizens? An Experience-Based Approach. Life (Basel). 11:161.
18. Lund JP, Donga R, Widmer CG, Stohler CS. (1991) The pain-adaptation model: a discussion of the relationship between chronic musculoskeletal pain and motor activity. Can J Physiol Pharmacol. 69:683-94.
19. Ruhe A, Fejer R, Walker B. (2011) Center of pressure excursion as a measure of balance performance in patients with non-specific low back pain compared to healthy controls: a systematic review of the literature. Eur Spine J. 20:358-68.
20. Berenshteyn Y, Gibson K, Hackett GC, Trem AB, Wilhelm M. (2019) Is standing balance altered in individuals with chronic low back pain? A systematic review. Disabil Rehabil. 41:1514-1523.
21. Yodchaisarn W, Puntumetakul R, Emasithi A, Boucaut R, Chatchawan U. (2018) Altered postural sway during quiet standing in women with clinical lumbar instability. J Phys Ther Sci. 30:1099-1102.
22. Mingorance JA, Montoya P, Vivas Miranda JG, Riquelme I. (2022) Differences in Postural Balance, Pain Sensitivity and Depression between Individuals with Acute and Chronic Back Pain. J Clin Med. 11:2700.
23. Knapstad MK, Ask T, Skouen JS, Goplen FK, Nordahl SHG. (2022) Prevalence and consequences of concurrent dizziness on disability and quality of life in patients with long-lasting neck pain. Physiother Theory Pract. 1-8.
24. Sremakaew M, Treleaven J, Jull G, Vongvaivanichakul P, Uthaikhup S. (2021) Altered neuromuscular activity and postural stability during standing balance tasks in persons with non-specific neck pain. J Electromyogr Kinesiol. 61:102608.
25. Ge L, Wang C, Zhou H, Yu Q, Li X. (2021) Effects of low back pain on balance performance in elderly people: a systematic review and meta-analysis. Eur Rev Aging Phys Act. 18:8.
26. Eker Y, Belgen Kaygısız B. (2019) The effect of pain severity on balance, postural stability and fall risk in patients with shoulder pathologies. Arch Med Sci. 17:390-396.
27. Petrofsky J, Donatelli R, Laymon M, Lee H. (2020) Greater Postural Sway and Tremor during Balance Tasks in Patients with Plantar Fasciitis Compared to Age-Matched Controls. Healthcare (Basel). 8:219.
28. Nogueira JF, Carrasco AC, Pelegrinelli ARM, Guenka LC, Silva MF, et al. (2020) Posturography Comparison and Discriminant Analysis Between Individuals with and without Chronic Low Back Pain. J Manipulative Physiol Ther. 43:469-475.
29. Hicks C, Levinger P, Menant JC, Lord SR, Sachdev PS, et al. (2020) Reduced strength, poor balance and concern about falls mediate the relationship between knee pain and fall risk in older people. BMC Geriatr. 20:94.
30. Mikkonen J, Leinonen V, Kaski D, Hartvigsen J, Luomajoki H, et al. (2022) Postural sway does not differentiate individuals with chronic low back pain, single and multisite chronic musculoskeletal pain, or pain-free controls: a cross- sectional study of 229 subjects. Spine J. 22:1523-1534.
31. Baratto L, Morasso PG, Re C, Spada G. (2002) A new look at posturographic analysis in the clinical context: sway-density versus other parameterization techniques. Motor Control. 6:246-70.
32. Tan L, Jiang J. (2019) Discrete Fourier transform and signal spectrum, In: Digital signal processing.91–142
33. Scoppa F, Capra R, Gallamini M, Shiffer R. (2013) Clinical stabilom-

etry standardization: basic definitions--acquisition interval-- sampling frequency. Gait Posture. 37:290-2.

34. Kapteyn TS, Bles W, Njiokiktjien CJ, Kodde L, Massen CH, et al. (1983) Standardization in platform stabilometry being a part of posturography. Agressologie. 24:321-6.

35. Scoppa F, Gallamini M, Belloni G, Messina G. (2017) Clinical stabilometry standardization: Feet position in the static stabilometric assessment of postural stability. Acta Med Mediterr. 33: 707.

36. Welch P. (1967) The use of fast Fourier transforms for the estimation of power spectra: A method based on time averaging over short modified periodograms. IEEE Transactions on Audio and Electroacoustics, 15:70-73.

37. Lephart SM, Pincivero DM, Giraldo JL, Fu FH. (1997) The role of proprioception in the management and rehabilitation of athletic injuries. Am J Sports Med. 25:130-7.

38. Doumas M, Smolders C, Krampe RT. (2008) Task prioritization in aging: effects of sensory information on concurrent posture and memory performance. Exp Brain Res. 187:275-81.

39. Goble DJ, Coxon JP, Van Impe A, Geurts M, Van Hecke W, et al. (2012) The neural basis of central proprioceptive processing in older versus younger adults: an important sensory role for right putamen. Hum Brain Mapp. 33:895-908.

40. Henry M, Baudry S. (2019) Age-related changes in leg proprioception: implications for postural control. J Neurophysiol. 122:525-538.

41. Anson E, Bigelow RT, Swenor B, Deshpande N, Studenski S, et al. (2017) Loss of Peripheral Sensory Function Explains Much of the Increase in Postural Sway in Healthy Older Adults. Front Aging Neurosci. 9:202.

42. Di Giulio I, Maganaris CN, Baltzopoulos V, Loram ID. (2009) The proprioceptive and agonist roles of gastrocnemius, soleus and tibialis anterior muscles in maintaining human upright posture. J Physiol. 587:2399-416.

43. Efstathiou MA, Giannaki CD, Roupa Z, Hadjisavvas S, Stefanakis M. (2022) Evidence of distorted proprioception and postural control in studies of experimentally induced pain: a critical review of the literature. Scand J Pain. 22:445-456.

44. Matre D, Arendt-Neilsen L, Knardahl S. (2002) Effects of localization and intensity of experimental muscle pain on ankle joint proprioception. Eur J Pain. 6:245-60.

45. Raud L, Thunberg C, Huster RJ. (2022) Partial response electromyography as a marker of action stopping. Elife. 11:e70332.

46. Smith LJ, Macefield VG, Birznieks I, Burton AR. (2019) Effects of tonic muscle pain on fusimotor control of human muscle spindles during isometric ankle dorsiflexion. J Neurophysiol. 121:1143-1149.

47. Le Pera D, Graven-Nielsen T, Valeriani M, Oliviero A, Di Lazzaro V, et al. (2001) Inhibition of motor system excitability at cortical and spinal level by tonic muscle pain. Clin Neurophy-siol. 112:1633-41.

48. Rossi S, della Volpe R, Ginanneschi F, Ulivelli M, Bartalini S, et al. (2003) Early somatosensory processing during tonic muscle pain in humans: relation to loss of proprioception and motor 'defensive' strategies. Clin Neurophysiol. 114:1351-8.

49. Carvalho GF, Becnel AR, Miske C, Szikszay TM, Adamczyk WM, et al. (2022) Postural control impairment in patients with headaches-A systematic review and meta-analysis. Headache. 62:241-270.

50. Tsigkanos C, Gaskell L, Smirniotou A, Tsigkanos G. (2016) Static and dynamic balance deficiencies in chronic low back pain. J Back Musculoskelet Rehabil. 29:887-893.

51. Oddsson LI, De Luca CJ. (2003) Activation imbalances in lumbar spine muscles in the presence of chronic low back pain. J Appl Physiol (1985). 94:1410-20.

52. Pirouzi S, Hides J, Richardson C, Darnell R, Toppenberg R. (2006) Low back pain patients demonstrate increased hip extensor muscle activity during standardized submaximal rotation efforts. Spine (Phila Pa 1976). 31:E999-E1005.