EFFECT OF THE VESTIBULAR SYSTEM ON SEARCH AND FALL BEHAVIOUR OF HUMAN POSTURAL SWAY

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ABSTRACT

EFFECT OF THE VESTIBULAR SYSTEM ON SEARCH AND FALL BEHAVIOUR OF HUMAN POSTURAL SWAY

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In a person's daily life, upright stance is a very essential postural position for using hands, locomotion, communication, etc. These motivations probably help a baby to solve this complex motor task faster. A healthy individual is thought to maintain his/her upright posture mainly by the help of four senses: vestibular, proprioception, vision, and somatosensory. With a classical view, human upright posture control mechanism is approached as a control system with multi inputs almost single output (CoPx). However, it is not only a classical mechanical control system with sensory inputs but also an *actively* acting system to drive perceptual information for exploring its environment. In this thesis, these active movements, with low-frequency characteristics, performed by healthy control subjects were named as a **search (benign) behavior** while the rapid corrections, with high-frequency characteristics, performed by bilateral vestibular loss (BVL) patients were named as a **fall (malign) behavior**. The contribution of the vestibular system to postural control was examined comparing the quiet stance CoPx signals of BVL and healthy subjects measured in different eye and surface conditions. Finally, results was discussed with an ecological perspective.

Keywords: search behavior, posture control, bilateral vestibular loss, action-perception theory, efferent copy, quiet stance

ÖZ

İNSAN DİK POSTÜR SALINIMINDA YOKLAMA VE DÜŞME DAVRANIŞINA VESTİBÜLER SİSTEMİN ETKİSİ

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Ayakta dik duruş, kişinin günlük yaşantısında ellerini kullanması, hareket etmesi ve iletişim kurması vb. sebeplerden dolayı vazgeçilmez bir öneme sahiptir. Bu motivasyonlar bir bebeğin bu karmaşık motor görevi muhtemelen daha hızlı çözmesine yardımcı olur. Sağlıklı bir insanın ayakta dik duruşunu temel olarak 4 duyusu sayesinde sağladığı düşünülmektedir: vestibüler, derin duyu, görme ve beden (dokunma) duyusu. Klasik bakışla, insan dik duruş kontrol mekanizması çok girdili hemen-hemen tek çıktılı (CoPx) bir kontrol sistemi olarak ele alınır. Bunun yanında, sadece duyusal girdileri olan klasik bir mekanik kontrol sistemi değil, aynı zamanda çevresini keşfetmek için algılayıcı bilgi elde etmek için *aktif* olarak hareket eden bir sistemdir. Bu tezde, sağlıklı (kontrol) denekler tarafından gerçekleştirilen düşük frekanslı bu aktif hareketler **yoklama (iyi huylu) davranışı**, çift taraflı vestibüler kayıplı (BVL) hastalar tarafından yapılan yüksek frekanslı hızlı düzeltmeler ise **düşme (kötü huylu) davranış** olarak adlandırıldı. Vestibüler sistemin dik duruş kontrolüne etkisi, farklı göz ve yüzey koşullarında ölçülen BVL ve sağlıklı bireylerin sakin duruş CoPx sinyalleri karşılaştırılarak incelendi. Son olarak, sonuçlar ekolojik bir yaklaşımla yorumlandı.

Anahtar Kelimeler: yoklama davranışı, dik duruş kontrolü, çift taraflı vestibüler kayıp, eylem-algı teorisi, eferent kopya, sakin duruş

Anneme ve Babama
Havva Cengiz ve Necdet Cengiz

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LIST OF ABBREVIATIONS

VOR	Vestibulo-ocular Reflex
VSR	Vestibulospinal Reflex
VCR	Vestibulocollic Reflex
CNS	Central Nervous System
DETES	Custom-Made Human Balance Testing Environment
CoP	Center of Pressure
CoPx	Center of Pressure in antero-posterior direction
CoPy	Center of Pressure in medio-lateral direction
Fx	X component of ground reaction force
Fy	Y component of ground reaction force
Fz	Z component of ground reaction force
Mx	Moment in x direction
My	Moment in y direction
Mz	Moment in z direction
QS	Quiet Stance
RS	Rigid Surface
CS	Compliant Surface
EO	Eyes Open
EC	Eyes Closed
Std. Dev.	Standard Deviation
BVL	Bilateral Vestibular Loss
PL	Path length
Var	Variance
R_{xy} or xCorr	Cross-Correlation Function
R_{xx} or aCorr	Autocorrelation Function
FFT	Fast Fourier Transform
PSD	Power Spectral Density
AuPSD	Area under the Power Spectral Density Function
Magmax	Maximum Magnitude of Absolute AuPSD

Fmagmax	Frequency corresponding to Magmax
μ_k	kth order Spectral Moment
CFREQ	Centroidal Frequency
FREQD	Frequency Dispersion
ANOVA	Analysis of Variance
HS	Healthy Subjects
EMG	Electromyography

CHAPTER 1

INTRODUCTION

1.1 Philosophical View

It is written: 'In the beginning was the **Word**.'
Here I am stuck already! Who will help me on?
To set so high a value on a 'word' is impossible:
I must translate it some other way,
If the spirit is giving me real enlightenment.

It is written: 'In the beginning was the **Mind**.'
Consider the first line well,
Let your pen not move on too fast!
Is it by Mind that all things are done and made?

It should read: 'In the beginning was the **Energy**.'
And yet, at the very moment of writing it down,
Something warns me not to leave it at that.
The spirit moves me! I suddenly see the answer,

and boldly write: "**In the beginning was the Deed.**"

This sonnet is from the "**Faust** of *J. W. von Goethe (1749–1832)* [1]. Probably, he was also trying to find answers to the hardest question in the world ever: What was in the beginning? This question was tough. Thus, he consulted the most trusted information source of his era, *The Gospel*. It starts with these revelations:

In the beginning was the Word,
and the Word was with God,
and the Word was God.
The same was in the beginning with God.

Since Faust, the main character of the book, was not a believer, *The New Testament* had not worth to translate as a holy writing. However, he thought that it was a precious base text to be construed. He believed that the thing in the beginning must involve all the information about life like the Greek word "**Logos**". Logos, in Greek philosophy, was a word which contains lots of meanings about the essence of the life. In certain beliefs, it has inclusive meanings such as "axis of the world", "core principle", "main reason" etc. Therefore, Faust compared all candidates for being the thing in the beginning with the Logos. The first candidate was the "**Word**". It may contain a meaning and an idea but not all essences, so "Word" cannot be put such a high value on. According to Faust, "Word" cannot express the whole integrity of meaning inside the Logos. Thus, he suggested a new candidate, "**Mind**". Here, the Mind refers to thought and sense. Faust was not satisfied with this description. He believed that sense and thought might only be the part of a universe but the whole. All things could not have been made or done by Mind, so the Mind cannot be the thing in the beginning. Then, he suggested the other candidate, "**Energy**". Faust felt a little misfit again. "Energy" has a relative meaning, but the thing should not be comparable. And finally, he confidently decided that in the beginning was the "**Deed**". This is because energy can only be appeared in the form of action. As a result, he concluded that *the Deed* can derive the whole information about the essence of the being or already had.

Probably, this impressive part of *the Faust* and its conclusion have inspired many thinkers for centuries. For instance, *Sigmund Freud*, the famous Austrian neurologist and the father of the psychoanalysis, have used this conclusive sentence in his book, *Totem and Taboo*, as a closing sentence [2]. Totem and Taboo is about the behavioral analysis of primitive man. In the book, Freud compare the relation between thought and the actions of them. Then, he states that there is no sharp difference between their actions and thoughts. Primitive man are not inhibited, the thought is directly converted into the deed. He also compare primitives' behavior with the behaviors of neurotics. In contrast to primitives, neurotics are all inhibited in their actions. For them, thoughts are completely substituted for the deed. After this discussion, Freud confidently states the priority between action and thought: In the beginning was the deed. Besides, *Alain Berthoz*, the French engineer and neurophysiologist, have started his book *The Brain's Sense of Movement* with the same sentence [3].

To sum up, at first all these thinkers had actually tried to understand different phenomena such as the beginning of universe, human behaviors, consciousness etc. However, after all their reasoning they came to same questions:
- What is the source of information?
- How the information arises?

1.2 Action & Perception

For many decades, perception has been one of the most attractive research topic in the world. Since *Aristotales*, it had been believed that individuals perceive the world by the help of five senses, namely taste, sight, touch, smell, and hearing but now it is known that there are other senses that help the perception of the world such as proprioception and vestibular system. All these senses except proprioception provide information from outside of the body to the central nervous system (CNS). On the other hand, proprioception is only sense that gives information inside the body, about the relative positions of one's own parts of the body. Sensory units responsible for the proprioception are called **proprioceptors**. There are three main kinds of proprioceptors: **muscle spindle**, **golgi tendon organ**, **receptors in joint capsules**. They provide information about skeletal muscle length, tension in tendon, and pressure, tension, movement at the joint, respectively [4]. A more detailed information about vestibular system was given in Section 1.3.1.

The ability to control the correctness of the actions of the living organism provides it a great advantage in the evolutionary process. This may be named as the awareness of its actions. However, all these sensations are only arriving signals that comes from receptors. On the other hand, the perception may be defined as the conscious awareness of these sensations. Another definition for perception from the view of motor theory of perception (**action-perception theory**) comes from *Berthoz*: Perception is an internal simulation of action. This means that perception is more than just the interpretation of sensory information. It is judgment, decision making, and anticipation of the consequences of an action [3]. In brief, motor theory of perception claims that perception is an active and action-related phenomena. In addition, there are many supportive studies published in order to show the relation between actions and perception in last a few decades [5] [6] [7] [8]. *Von Holst* and *Mittelstaedt* suggest a schematic diagram to explain addition of the motor actions to the perception with the concept of *efferent copy* [9]. (see Figure 1.1)

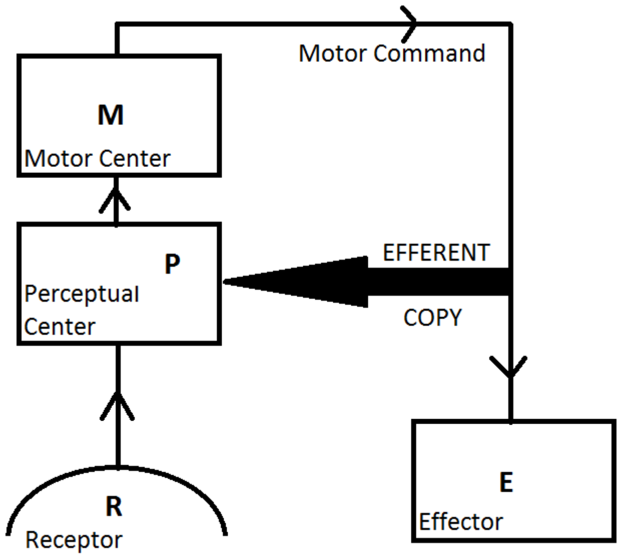

Figure 1.1: A schematic diagram for efferent copy

Figure 1.1 demonstrates that signals coming from the receptor are sent to a neural center (P) where perception is derived. In this state, P has only sensation. At that time, a motor neuron (M) is also fired through a loop from motor center to the effector organ (the muscle). However, a copy of the motor command is also sent to the perceptual center, where it changes sensory information according to the ongoing action. In this state, perception is derived. Thus, brain is able to anticipate the consequences of the action without having to wait for information about the end of the action.

Like the all other motor behaviors, one's postural control performance is related with one's perception. In this study, subjects were tested in upright posture and quiet stance (QS) condition. According to motor theory of perception, the more one perceives his/her body movement and orientation, the more successful he/she is in the test. The schema in Figure 1.1 illustrates also that in order to have a flawless perception one needs to collect and process signals clearly, coming from the pathways of efferent copy and receptor to the neuron responsible for the perception.

1.3 Human Upright Posture and Its Sensorimotor Control

Although maintaining the upright stance is one of the most important and basic requirements in the daily life of humans, there is no universal agreement for the definition of the posture and balance. However, human posture may be defined as voluntarily oriented absolute positions of the body and limbs relative to each other and relative to the space they are in. These position information can be divided two part: position with respect to body and position with respect to ground.

A healthy individual maintains his/her upright posture mainly by the help of **four senses**: vestibular, proprioception, sight, somatosensory. Among all these, proprioception is the only **interoceptor** which sense position with respect to body while, the other sensors gather information from outside of the body and classified as **extoreceptor**.

For many years, human motor control system is approached as a classical mechanical control problem with multi inputs single output. However, the idea that motor control problems, i.e. human upright posture control, cannot be treated as such a control problem has led the researcher in many fields to direct attention to this topic in the last century [10] [11] [12]. Designing controlled experiments for understanding sensorimotor control of upright stance has certain difficulties. For example, it is not possible to shut off any of the four senses listed above, except the eye voluntarily.

Thus, clinical studies performed on patients with sensory loss become essential to observe the effects of these senses on the posture control separately [13] [14] [15].

After philosophical literature above, it is impossible to discuss posture and postural control regardless of the relation between information and *the Deed*. It is known that each healthy individual has lots of sensory organs for gathering information in order to perform motor task but it is not clear that postural control may be achieved by the help of only passive sensations [16] [17]. An individual may need to act personally in order to learn a motor task. This is compatible with the schema in Figure 1.1, because motor actions may develop perception through efferent copy. Then, it feeds back motor actions. For example, when babies try to get up and keep their balance, they fail to do it repeatedly. During this "*trial and error*" period, multisensory inputs in their brain are integrated with efferent copies in each trial and they gradually learn to stand up. *Berthoz* defines "the first standing up of a baby" as the most difficult motor control problem solved in a persons entire life [3]. Another important point is whether it is possible under all circumstances to obtain information from the action. And, does it depend on any certain conditions?

In the majority of posture control research, the main signal analyzed is the center of pressure (CoP). It is explained in detail in Section 4.1. During a QS trial, CoP of a healthy person travels with non-linear characteristics inside a circle with radius of 1cm (see Figure 4.2) [18] [19] [20], while travel of CoP of a patient with sensory loss such as bilateral vestibular loss (for detailed information, see Section 1.3.1.2) demonstrates different sway characteristics. Finding the reason(s) of this difference is important to solve sensorimotor organization of posture control [21]. The questions are "where does this change come from" and "can this change be followed through CoP signal?" Adapting the concept of efferent copy into the posture control problem provides some advantages for interpretation of this problem. The first one is to explain relation between perception and motor performance. As mentioned above, sensory loss may cause a change in information flow which is critical for the integration of perception. Since this change in perception effects the motor behavior of people, a new sway characteristic arises. For example, patients with BVL tend to fail more than healthy people in predicting platform movements in tilted experiments [22]. In addition, their CoP patterns were different in QS trials. This was discussed in detail in the discussion part. As a result, it is known that the change in postural control performance follows the perceptual deterioration in BVLs.

Another advantage is about its visual contribution to postural control. *Nashner and Berthoz* had been around for a paper presentation in an international physiology conference. Interestingly, although their studies were about the same topic, their arguments were completely against each other. According to *Nashner*, null-vision did not play role on postural reactions whereas *Berthoz* claimed that it had an important role. After their debate, they decided to design an experimental setup to test the contribution of the null-vision on upright posture. In the experiment, subjects would not close their eyes but the setup would stabilize the visual world in a transitionally manner. Thus, the brain would not perceive any movement by vision. Only the proprioception of the muscles and the joints, along with the vestibular sensors, perceived the movement. The result verified Berthoz's expectations. Compensatory reactions were not observed in the condition of lacking visual information compared to "closing the eyes" condition. According to *Berthoz*, when a subject closes his/her eyes, the brain actively reorganize the configurations of sensors on which it bases its decisions and expectations. In other word, closing the eyes voluntarily changes the state of sensory fusion due to efferent copy signal [23] [3]. In addition, the number of examples for effects of voluntary action on the state of sensory fusion can be increased with a daily life experience. For instance, a ticklish person can be tickled by another person but he cannot get tickled by himself. This is because before consequences of the action occur, the copy of the motor command informs about the action [16]. This phenomena is also called as "**sensory channel reweighting**" by *Peterka* [24].

Interpreting the consequences of loss of vestibular system compared to one of the five senses is much more complex due to its interconnections with other senses and contributions to the highest cognitive functions [25] [26] [27] [28]. Vestibular signals do not remain at the level of the *first sensory relays*. It is also transmitted to the cerebral cortex, where it contributes to many functions: conscious perception of orientation, gaze movements, control of posture, and coordination of gestures. Moreover, its another important contribution is constructing a coherent perception of relationship between the body and space. This is also closely related with grounding the self-perception. Vestibular signals are evaluated in vestibular nuclei. Among various neurons in the **vestibular nuclei**, there are some very special neurons called **the second-order vestibular neurons**. Actually, it is a sensory neuron where sensory inputs coming from eyes, vestibular, and proprioception are fused. However, it is also a motor command neuron because it can directly stimulate the ocular motor neurons, and in some case the neck muscles. In addition, these neurons may be thought as a local decision making station for some autonomous motor functions due to their sensory fusion ability. This ability is also essential to construct a coherent perception of the body or of its relationship with the environment [3].

Perception of movement can be analyzed to understand the importance of the coherence. In physics, the main problem for defining the movement is relativity. Physicists solve this problem by choosing a reference point. However, the brain's way of solution is different. To decide who is the acting, the self or environment, it uses the fused (compared) sensory signals. Proprioception, especially the muscle spindle, plays an important role in this comparison. The information of self-generated action is carried by the proprioception [29]. Thus, one can perceive that the action was done by self if other sensory inputs are also included into fusion properly.

In posture control, same ambiguity exists for distinguishing the body sway due to self-perturbation from the body sway due to external forces, i.e. gravitation. Postural perception arises from the interpretation of these two dynamics that constitute postural sway by the brain. Vestibular system plays role to measure and evaluate these postural movements. Postural perception of patients with BVL deteriorate because the sensory fusion does not occur properly due to lack of information flow. These impairments influence the postural control performance directly. In this thesis, one of the most important aims is to determine this loss of information through the analysis of CoP signals of BVL's and HS's. In brief, postural control is not a classical mechanics problem controlled by the help of passive sensations. One's sensations that contribute to postural control are regulated by one's own postural actions. This regulation changes the interpretation of sensory information. Thus, it is also related with one's perception. As a result, one's postural performance also depends on one's self-perception.

1.3.1 Vestibular System

The history of vestibular system starts with the *Casserii's* publication on the description of the bony labyrinth in 1610. A more detailed description of the inner ear organs was published by *Scarpa* in 1789 [30]. The descriptions of the microscopic anatomy and the inner ear innervation were published in the late 1800s [31]. Since the information receiving from the vestibular organ is not easy to perceive consciously, its functions cannot be noticed by observation. It distinguishes vestibular organ from the five senses. On the contrary the sensation of muscle proprioception reaches "conscious awareness".

Vestibular organ, shown in Figure 1.2 [29], is a sensory organ which measures gravitational and inertial forces and converts a signal that drives our motor system for many cases such as gaze stabilization and balance. In addition, it controls our head directions with respect to gravity. These behaviors are unconscious and automatic actions. In the case of dysfunction of vestibular system, people lose their gravitational reference and thereby loses their balance. This is generally defined as an overwhelming feeling by the patients because they suffer from nausea, vomiting and vertigo. Vertigo is a perceptual problem due to a conflict between the vestibular input and the other sensory inputs (esp vision). Patients with vertigo feel rotation, as either the self or the room is spinning, even they are stationary.

The stimulus for the vestibular system are head acceleration and rotation. These two movements are measured by the aid of five different structures, namely otolith organs (**utricle** and **saccule**), three **semicircular canals** (lateral, anterior and posterior). **Otolith organs** are responsible to sense linear (translational) motion whereas semicircular canals sense angular motion of the head in three dimensions (see Figure 1.2). Each of the five receptor organs has a cluster of **hair cells** responsible for transducing head motion into vestibular signals. These hair cells, shown in Figure 1.3 [32], are sensitive to mechanical stimulus. For linear acceleration, hair cells are triggered mechanically by the otoliths containing inside the utricle and the saccule. Otoliths are also called as ear stones since they are composed of dense calcium carbonate particles. These particles bend the hair cells depending on the direction of movement towards either **kinocilium** (preferred direction) or **stereocilium** (non-preferred direction). If

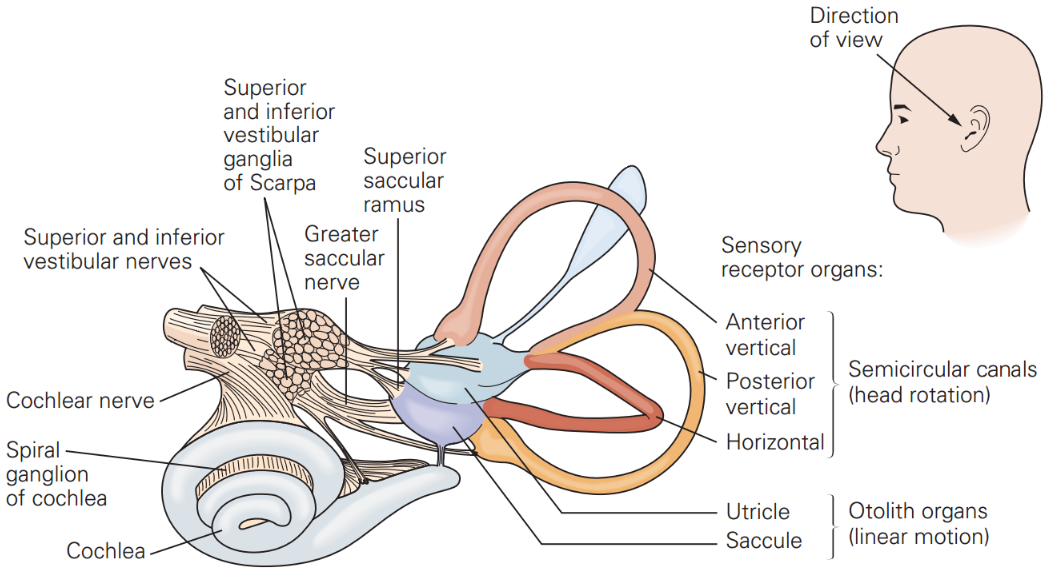

Figure 1.2: Vestibular Organ

they bend towards to the preferred direction, the ion channels are opened by the help of tip link mechanism and afferent nerves are excited otherwise the ion channels are closed and nerves are inhibited. The resting membrane potentials of vestibular nerves are about -40 mV, higher than general membrane potentials (-60 mV). This property makes it sensible to measure motion in either direction.

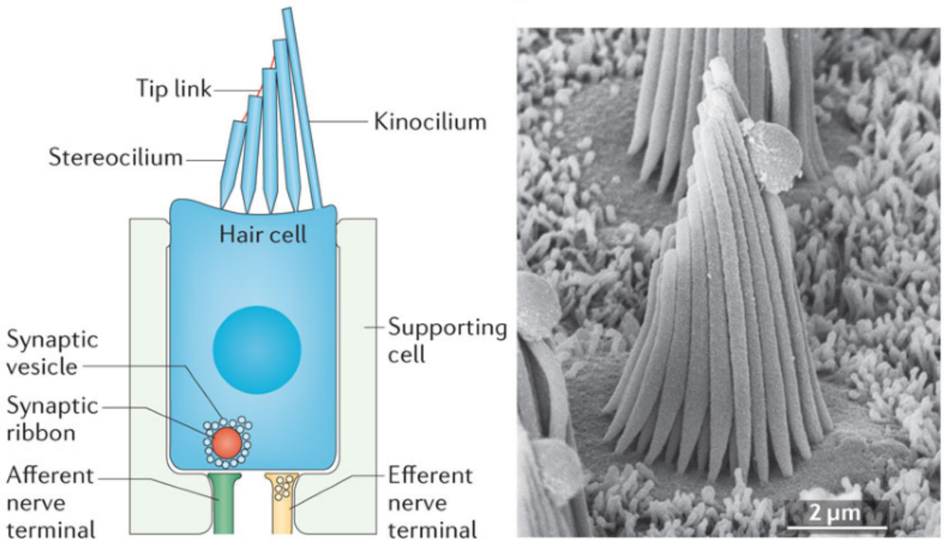

Figure 1.3: A hair cell

Moreover, angular motions are sensed with a similar way by semicircular canals which utilize a kind of viscous fluid inside semicircular canals. When the head is rotated, fluid moves to opposite direction due to inertia. This relative motion of fluid allows individual to sense angular acceleration in any rotation.

If the semicircular canals do not work well, perceptual problems like vertigo occurs. Besides, if there is a problem with linear acceleration sensors, disequilibrium in balance occurs. For instance, balance in elderly people change with time since the sensibility of sensor diminishes based on decreasing density of otoliths.

The information received from the vestibular system is also used after integrating with other senses, i.e. it is fused with visual information in the vestibular nucleus in order to discern the slow movement of the eyes which is an unconscious process. For example, perceiving the "absolute" movement is not easy in case that a person is sitting in one of two trains stayed side by side while looking at the other train (vection problem or the problem of "self-motion", which are not relative motion but the motion with respect to an "inertial" frame of reference; motion in the sense of Newton). If the person feels a slow movement, he/she cannot be sure which train moves because the vestibular apparatus has a **threshold** acceleration under which one cannot sense any movement. In brief, vestibular system needs a little bit movement to get enabled to measure.

1.3.1.1 Vestibular Reflexes

Another important function of vestibular system is the gaze stabilization. Gaze movement is defined as the sum of head and eyes movements. Maintaining the gaze is actually a tough process which is controlled by the **Vestibulo-ocular Reflex (VOR)**. For example, although our heads swing around while we are running, it does not cause any deterioration in our gaze. This is because VOR sends signals to control eyes muscles in order to cancel out the head movement. However, the VOR must be adapted depending on the distance of the focused thing. For instance, the eyes movements needed to stabilize the gaze onto farther things are smaller than closer things. This reflex modulation is automatically controlled by the **flocculus** which is a part of the cerebellum. Another modulation (cancellation) of the VOR is needed to change the direction of the gaze otherwise eyes keep always looking to the same target. When the VOR is cancelled to allow the eyes to change the gaze, they do a ballistic movements, called **saccade**, towards new target. Its velocity is about 300-400 °/s. This movement is controlled by the brain stem. If once a target appears, the saccade starts roughly 200 ms later. Once a saccade starts, even if the target shifts the saccade ends up on the place planned to go. Saccades are needed to look around the world but it may be damaged in people who are in certain disorders like bilateral vestibular loss. In this case, some gaze stabilization problems occur depending on the disfunction of the VOR, and unwilling saccades increases. This symptoms are used to diagnose patients.

Moreover, there are other reflexes related with the vestibular system. One of those is the **Vestibulospinal Reflex (VSR)** whose aim is to stabilize the body. Impulses transmitted from the vestibular system to the spinal cord at the moment when the head is tilted cause to induce muscles in order to straighten the head. Another reflex for the head stabilization is the **Vestibulocollic Reflex (VCR)**. Its pathways are not known well but it is known that VCR acts on the neck muscles [33].

1.3.1.2 Bilateral Vestibulopathy

The bilateral vestibular loss is defined as reduction or absent of vestibular function on both sides due to deficits either in the labyrinths, in the vestibular nerves, or in both [34]. BVL probably represents a functionally heterogeneous disorder with different combined or isolated deficits of the semicircular canals and/or otolith organs [35]. Despite of increasing etiological studies, its etiology still remains unclear in approximately 50% of all cases [36] [37]. It is rare, but results in impairment or loss of the major functions of the vestibular organs: gaze stabilization, maintaining balance, postural control and spatial orientation. Common symptoms of BVL are oscillopsia due to impairment of VOR, autonomic symptoms, chronic disequilibrium, postural instability and impaired spatial orientation [38]. Postural instability problem of these patients cause impairment in their quality of life because it affects the management and the level of independence of these patients. Some studies demonstrate that the fall risk increases in BVL patients [39] [40] [41].

The diagnosis of BVL is routinely established by the head-thrust test, caloric irrigation and rotational testing with **electronystagmography** to determine the high- and low-frequency deficit of the vestibulo-ocular reflex. These three methods evaluate semicircular canal function only. In addition, **vestibular-evoked myogenic potentials (VEMPs)** provide a measure of saccular otolith function [35].

1.4 Hypothesis & Scope of Thesis

The first inspiration to begin this thesis is the results of the experiments conducted by *Horak, Nashner and Diener* [42]. They have examined the role of vestibular and somatosensory (proprioception included in) information on postural responses by comparing postural responses of healthy control subjects separately with subjects' with somatosensory loss and subjects' with vestibular loss. They found that somatosensory loss resulted in an increased hip strategy for postural correction while vestibular loss resulted in a lack of hip strategy but normal ankle strategy. Thus, they concluded that somatosensory information from the feet and ankles may play an important role in assuring that the form of postural movements are appropriate for the current biomechanical constraints of the surface and/or foot while the vestibular information is necessary in controlling equilibrium in a task requiring use of hip strategy.

In addition, two studies of *Mergner's* group were the other sources of inspiration [21] [43]. The main idea of these studies is that vestibular system provides a sensory information to decompose the body sway to its two components: self- and external-generated components.

If posture control is approached as a classical mechanical problem aiming to stand stationary in gravity vertical (setpoint), then the deviation from the setpoint is defined as error. On the other hand, this error is taken as a source of information in ecological approach of motor control. All above about motor and postural control demonstrate that actions and movements may be useful for postural motor performance. One's body sway in upright posture may be a source of information to maintain one's stability of posture. From an ecological perspective, this idea is analogically similar with the search behavior of the some kinds of insects [44] [45] [46] [47].

Inspiring the lack of hip strategy in *Horak's* results and the *Mergner's* idea, we hypothesized that exclusion of vestibular information from postural control alters the postural dynamics due to missing ability to decompose self- and external generated components of body sway. With an ecological view, we also claimed that vestibular information impose a **search (benign) behavior** into postural sway to explore the environment stayed in. This exploration allows people to adapt to new environment by the help of information included in deed. Since BVLs lack vestibular information, they were expected not to perform this search behavior but **fall (malign) behavior** in changing testing environments. Finally, it is suggested that the action (deed) is necessary to maintain postural stability with an ability of adaptation. This action arises from the interaction of vestibular and proprioceptive information.

In this thesis, only the CoPx signals of trials performed in QS were examined in order to demonstrate the missing search behavior in the postural sway of BVL patients comparing with healthy subjects'. Subjects were tested in both EO/EC and RS/CS conditions. Then, metrics calculated through CoPx signals were analyzed to reveal missing postural dynamics in BVLs'.

CHAPTER 2

EXPERIMENTAL SET-UP

Experiments were performed in Posturography Laboratory at Otorhinolaryngology Department of Gülhane Military Medical Academy. This laboratory has a human balance system testing environment (DETES). In this chapter, DETES and its components are introduced.

2.1 Custom-Made Human Balance Testing Environment (DETES)

DETES is an originally designed custom-made human balance testing environment. It was installed at the Posturography Laboratory at Otorhinolaryngology Department of Gülhane Military Medical Academy in 2014. Its development process dates back to about ten years ago. Motivation to build this laboratory was to investigate complex control mechanism of human erect posture and to understand contribution of four sensory afferent systems (vestibular, visual, somatosensory and proprioception) to postural control separately [48].

After the electro-mechanical and electronic components had been installed by our team, we developed a software for initialization and control of tilting platform. Besides, safety preventions in order to protect subjects against injuries during experiments was added to system. Then, the software were adapted in compliance with experimental protocol.

DETES is composed of five main components: tilting platform, tilting cabinet, force plate, motion capture system and data acquisition tool.

2.1.1 Tilting Platform

The tilting platform, shown at Figure 2.1a, was designed as circular plate which has 2-dof (antero-posterior and medio-lateral) tilting ability. It can pursue a sinusoidal input with frequency between 0.05 – 2 Hz and peak amplitude between 1°- 10°. The distance between rotation axis of the tilting platform and rotation axis of the ankle of a subject is about 34.5 cm.

2.1.2 Tilting Cabinet

The tilting cabinet, shown at Figure 2.1b, was designed to cover all around the tilting platform with a black curtains. It allows carrying out experiments inside the cabinet in dark environment. The cabinet has also 1-dof (antero-posterior) tilting ability with the same frequency response and peak amplitude.

Figure 2.1: Xsens MVN BIOMECH motion capture system and an inertial sensor

For the emergency, all subjects were fastened with safety harness to the ceiling. Besides, there are two holders fixed to the supporting table. Subjects were told that if they have any problem during tests, they can grasp holders. Under such circumstances only that section of experiments were canceled and repeated.

Tilting components were driven by AC servo motors (1.5 kW maxpower, 4.77 Nm max torque capacity, 3000 revolution/minute), Allen-Bradley© OEMax (RD15-A), and servo motor drivers, Allen-Bradley© CSD3. Servo motors have quadrature encoders whose resolution is 2500 pulse/revolution. Since angular velocity needed at tilting experiment is much less than generated by servo motors, reducers of x80 has been used to decrease angular velocity. Reducers are also increase the torque of actuators.

In addition, an electronic card (cRIO© 9073) and a software (Labview®) developed by National Instruments are used to control tilting platform with a desktop computer.

2.1.3 Force Plate (Ground Reaction Forces Measurement)

Ground Reaction Forces were measured by a Bertec© FP4060 Force Plate with a Bertec AM6800 signal amplifier. It collects three ground reaction force signals (Fx, Fy, Fz) and three moment signals (Mx, My, Mz) in three axes (x, y, z). These axes are shown in Figure 2.2. Here, Fz is the force applied by the subject to the force plate vertically. This vertical force is also equal to the weight of the subject when he/she is in quiet stance. The other forces, Fx, Fy, are the friction forces between force plate and feet of the subject in the antero-posterior and medio-lateral direction, respectively (Figure 2.2).

Besides, Mx and My give the moments caused by body fluctuations of the subject with respect to the axes given in Figure 2.2, while Mz gives the torsional moment applied by the subject. All this information is valid for quiet stance experiments. While the platform is tilting, the inertial effects must be considered.

In this study, the main signal, which is calculated from the kinetics (force plate) data (Fz, Mx and My), is the center of pressure (CoP) signal. Thus, the force plate signal is the most important data collected for this thesis. Calculation and detailed definition of CoP were given in Section 4.1.

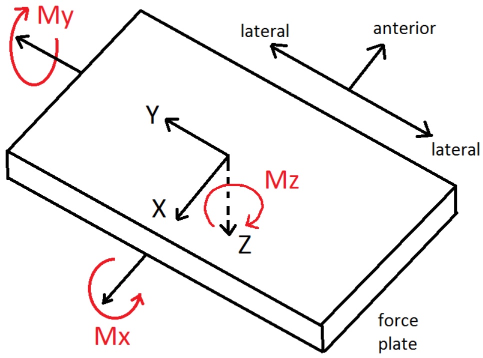

Figure 2.2: Force and moment directions of force plate

2.1.4 Motion Capture System (Xsens MVN BIOMECH©)

Xsens MVN BIOMECH© is a human motion capture system which consists of 15 inertial sensors. In these inertial sensors there are separate measurement devices to measure acceleration, angular velocity and the magnetic field vector. The system and its inertial sensor are shown in Figure 2.3.

The system gives options to use data collected as both version, raw and adjusted based on its own biomechanical model. Xsens uses magnetic field vector for calibration and it calculates estimation of the sensor's orientation with respect to a global fixed coordinate system. Xsens MVN BIOMECH© stores this orientation data as quaternion matrix, a kind of rotation matrix, or Euler angles. Then, this kinematics data is used to compute relative and absolute positions of the foot, limbs, trunk and head in three dimensional space [22].

2.1.5 Data Acquisition Tools

There are two computers used for collecting kinematics and kinetics data. One of them is the main computer into which MATLAB© is installed. This computer is responsible for collecting kinetic data measured by force plate. Besides, it sends a trigger signal to other computer in order to start collecting kinematics and kinetics data simultaneously. It also sends another analog signal to the NI cRIO 9073 to organize the experimental protocol. Shuffling the order of the experiments, MATLAB©

Figure 2.3: Xsens MVN BIOMECH motion capture system and an inertial sensor

assigns the experimental protocol. Detailed information about experimental protocol was given in next chapter. The other computer, into which MVN Studio is installed, is responsible for collecting kinematics data measured by Xsens. Both kinetics and kinematics data are collected with 100 Hz sampling rate in real time.

CHAPTER 3

EXPERIMENT & PROTOCOL

Participants performed 20 trials throughout the experiment. Experiment consists of two main parts. First was the quiet stance (QS) experiment part. Second was the tilted experiment part. First part was also composed of two parts, rigid surface (RS) experiments and compliant surface (CS) experiments. These trials were performed in eyes open (EO) and eyes closed (EC) conditions. Each kind of trial was repeated three times. However, rigid surface trials were not repeated. It was explained in Section 3.3.1.1 in detail. The order of the parts have not been changed but trials in compliant surface part and tilted part were shuffled within the parts. This operation was done by MATLAB© at the start of the experiment automatically.

At first, eyes open and closed trials on rigid surface were performed respectively in order to record natural postural fluctuation characteristics of the subjects. Then subjects completed the compliant surface part and the tilted part respectively. There was a ten seconds break between each trial except for the breaks when the surface was changed. In this period, system paused collecting data from both sensors. Additionally, whenever the subject demanded a break for resting, trials were ceased immediately. This did not cause any problems for the tests because such trials were canceled and repeated after a while. Again, this operation was done by MATLAB© automatically.

Moreover, there was a preparation period for the experiment. Although the data collection period is about 25 minutes, whole experiment took about 90 minutes with preparation and interview sections. Thus, these progresses were mentioned separately in next sections. In addition, a flow diagram is given for the experimental progress at the end of the chapter in Figure 3.5.

3.1 Preparation of Platform

Initialization of the tilting platform, setting the platform as parallel to the ground, is a crucial process to obtain reliable data. There are two proximity sensors placed to the ground as shown in Figure 3.1. When the system is started up, embedded Labview© code finds its parallel position with respect to the ground using these proximity sensors. After initialization, a rubber-like mat, shown in Figure 3.3, was laid on the force plate in case subjects' feet were cold as it is metal.

Finally, force plate signals were reset through the amplifier. When the platform was ready, we started to prepare subject to the test.

Figure 3.1: Side views of the tilted platform with proximity sensors

3.2 Preparation of Subject

Before we started to prepare the subjects to the test, we had asked some questions about their diseases and life styles. Taking medical history of subject made it easy to interpret the data. List of questions asked before and after the experiment was given as a list in Appendix C.

The longest period of preparation is the period of clothing of the motion capture dress to the subject. As it is shown Figure 3, each of 15 inertial sensors should be tied onto the place given in the manual carefully. Subjects were also tied a body harness for security. After clothing and cable connections process of motion capture system, it must be calibrated before data collection. For the calibration, height of subject and length of the subject's foot were entered to MVN Studio software. Finally, participants were asked to stand with a certain posture based on instructions given for the calibration in the manual. After calibration, participants were asked to take a comfortable position for test on the platform. Then, their body harness' were tied to the ceiling with a rope. Face direction was towards the black curtain which was stretched around the cabinet.

Participants were also given some necessary instructions just before the start of experiment. For example, they were asked not to move voluntarily. This was very important because we aimed to measure the natural body oscillations of the subjects. Moreover, they are instructed that commands given by the operator must be followed carefully such as eyes open, eyes closed etc.

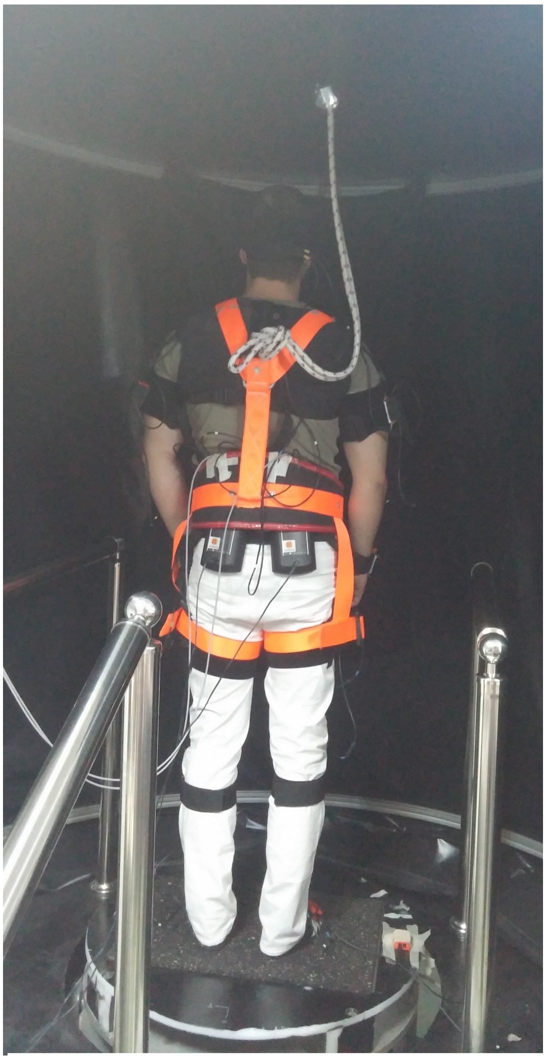

Figure 3.2: A picture from Experiment

3.3 Experimental Parts

3.3.1 Quiet Stance Part

There were eight quiet stance trials of 45 seconds. First two of them were rigid surface trials and the remained six were compliant surface trials. In this part, platform was stationary. Then, fluctuations of the participants due to self-perturbations of the subjects were measured in eyes open and eyes closed conditions.

3.3.1.1 Rigid Surface Trials

These trials set is called as rigid surface trials because they were performed on the rubber-like mat, whose size is the same with force plate (40 cm x 60 cm) and laid on force plate. Since rigid surface trial is the most similar test with upright posture of subjects in real life, it was assumed as the natural (reference) postural behavior of the subjects. These trials were not repeated since they were assumed as "habituated" behaviour of the subjects. Also, they were not shuffled within the first part of the test due to the fact that compliant surface trials would change the postural behavior due to learning effect and/or transient behaviour. (Figure 3.3).

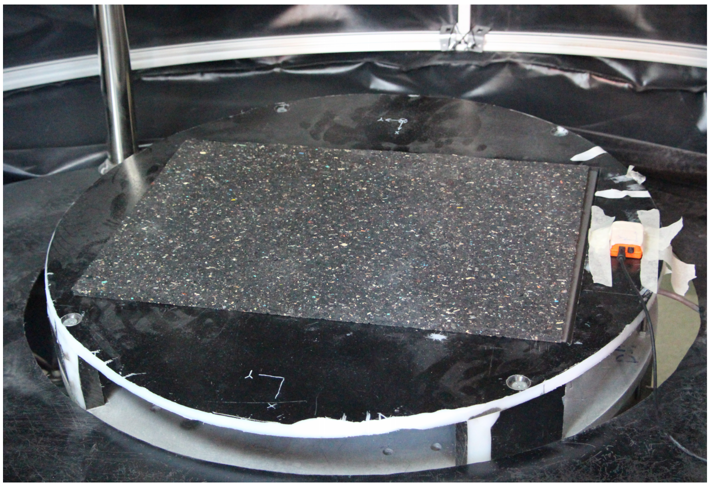

Figure 3.3: Rigid support surface

3.3.1.2 Compliant Surface Trials

On the other hand, a new sponge-like support surface, as shown in Figure 3.4, was added onto the rubber-like surface after rigid surface trials were finished. In this part, platform was still stationary. Eyes open and eyes closed trials were repeated three times. These six trials were shuffled for each participant. The purpose of trials with compliant surface was to provoke the foot somatosensory of subjects. It serves to interpret the relation between postural behavior and sensory information coming from tactile receptors and eyes. Besides, it gave an opportunity to compare patients and healthy subjects with reduced tactile information.

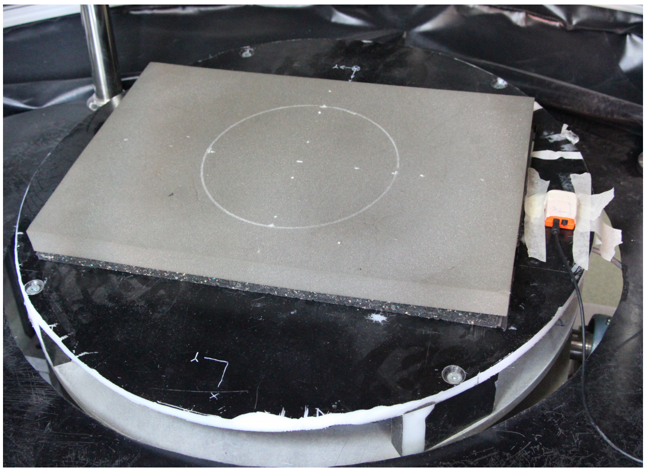

Figure 3.4: Compliant or sponge-like support surface

3.3.2 Tilted Part

This part is not in the scope of this thesis. It was studied within the scope of another thesis [22]. In brief, platform was tilted with two types of frequency, 0.05 Hz (F1) and 0.17 Hz (F2). The amplitude (1°) was not changed. This part was composed of 12 shuffled trials together with their repetitions, namely 3 eyes open F1 trials, 3 eyes closed F1 trials, 3 eyes open F2 trials and 3 eyes closed F2 trials. Measurement durations of F1 and F2 trials are 100 seconds and 30 seconds, respectively. These 12 trials were shuffled for each participant too.

3.4 Interviewing with Subject about Experiment

After the whole trials had been performed, motion capture suit was removed and the subjects were asked some questions about the experiment. This questioning part was the most important part in order to interpret the data collected because subjects' expressions helped to give new meaning to the data. Otherwise, explaining different behaviors and strategies of subjects would be more complex.

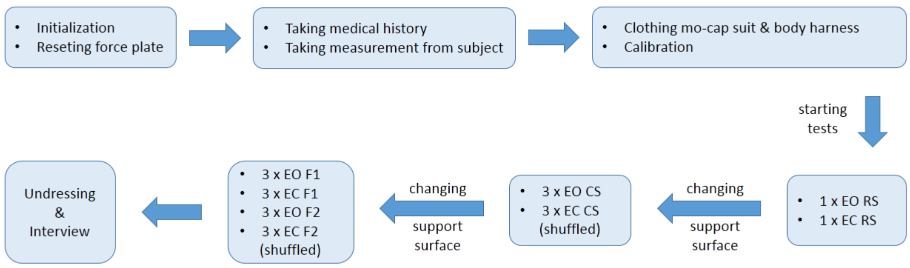

Figure 3.5: Flow diagram for experimental progress

Table 3.1: Descriptive Statistics Table for Subjects' Age and Body Measurements

Measure	Subject	Mean	Std. Dev.
Age	HS	45.2	13.6
	BVL	32.4	10.5
Height (cm)	HS	163.3	6.7
	BVL	165.7	5.2
Weight (kg)	HS	77.8	18.4
	BVL	73.9	12.3
Foot Size (cm)	HS	24.8	0.6
	BVL	24.3	1.1

3.5 Subjects

There are two main participant groups in this study, bilateral vestibular loss patients and control group (healthy subjects). Each group consists of seven participants (six female, one male). Control group was chosen among voluntary people. On the other hand, BVL subjects were accepted from the patients who consulted to the Otorhinolaryngology Department of Gülhane Military Medical Academy. These peoples also joined to this study voluntarily. Some statistics for subjects were given in Table 3.1.

CHAPTER 4

DATA ANALYSIS METHODS

The scope of this thesis is analyzing for only the quiet stance trials. The tilted part was also studied in another thesis [22]. Since the tilted part was not included, only ground reaction forces and moments signals were used to be analyzed. The force plate data was used to calculate center of pressure signal, the basic balance metric.

4.1 What is the Center of Pressure (CoP) Signal?

Although the platform is stationary, all people have a trace of postural sway due to self-perturbation. This sway changes the spatial position of the **Center of Mass (CoM)** of subjects, about 1 meter high from the ground. However, CoP is not a simple/passive projection of the CoM of the subject to the horizontal xy-plane; rather can be interpreted as a control signal of the center-of-mass of the body [49]. It also does not give information about the force distribution exerted to the ground by feet but the location of application point of the resultant force-couple system. Its time series, variation, is the most commonly used metric to investigate control of the human erect postural dynamics. Since it is measured from a plane, it has two components, CoPx and CoPy. While CoPx is the location of CoP on the antero-posterior direction, CoPy is the location of CoP on the medio-lateral direction. The representative plot of CoPx of a healthy subject was given in Figure 4.1.

As shown in Equation 4.1 and 4.2, these two components can be calculated using three force plate signals, Fz, Mx, My. Since we collected the data through 45 seconds

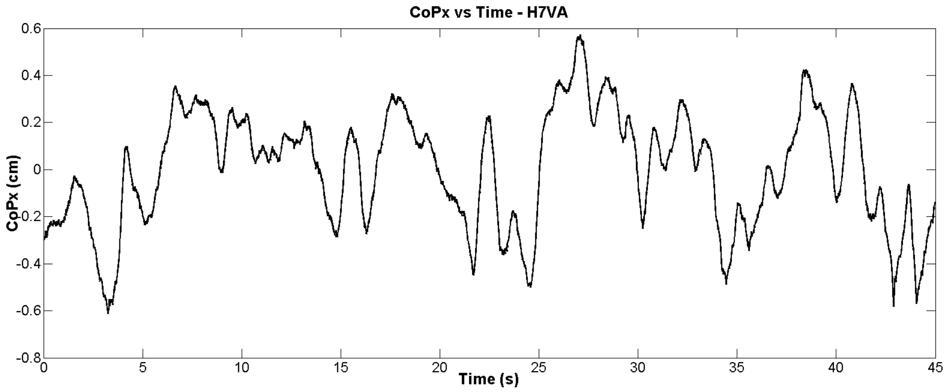

Figure 4.1: A Sample Plot of CoPx vs Time

with 100 Hz, the array size of each trial was 4500.

$$CoP_x(i) = \frac{-M_y(i)}{F_z(i)}, i = 1...4500 \tag{4.1}$$

$$CoP_y(i) = \frac{M_x(i)}{F_z(i)}, i = 1...4500 \tag{4.2}$$

This time series signals, from which is derived metrics to describe human postural sway, was analyzed in both time and frequency domains. Before the analysis, linear detrend had been applied to the CoP data.

4.2 Time Domain Analysis

4.2.1 Path length (PL)

Path length is defined as the total distance traveled by CoP over the horizontal plane during a trial [50]. This travel can be shown by plotting the CoPx vs CoPy (See Figure 4.2). It represents the sum of whole postural movements in both antero-posterior (x) and medio-lateral (y) directions. The calculation of PL was shown in Equation 4.3.

$$PL = \sum_{i}^{n} \sqrt{(CoPx_{i+1} - CoPx_i)^2 + (CoPy_{i+1} - CoPy_i)^2}, i = 1...4500 \tag{4.3}$$

The most important difference of this metric from others is that it includes the information about whole movement over the horizontal plane. Other metrics were calculated only for the CoPx signal, movement on the unstable axis that is antero-posterior axis.

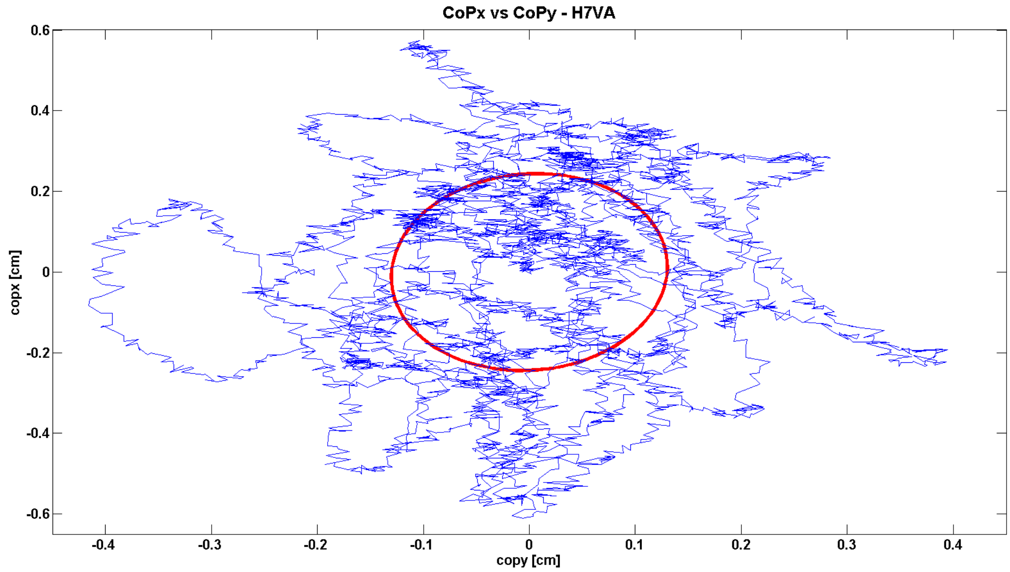

Figure 4.2: A Sample Plot of CoPx vs CoPy

Moreover, the 95% confidence ellipses were plotted with red line for each subject, as shown in Figure 4.2. The areas of these ellipses were calculated to compare sway areas of subjects.

4.2.2 Variance

Variance is a strong statistical measure which gives idea about how far a data set is spread out from its mean. The mean and variance of a CoP time series were calculated as given Equation 4.4 and 4.5, respectively.

$$Mean(CoP) = \overline{CoP_{x,y}} = \frac{1}{n}\sum_{i}^{n} CoP_{x,y}(i), i = 1...4500 \tag{4.4}$$

$$Var(CoP) = \sigma^2_{CoP} = \frac{1}{n-1}\sum_{i}^{n}(CoP_i - \overline{CoP})^2, i = 1...4500 \tag{4.5}$$

4.2.3 Cross-Correlation (xCorr) and Autocorrelation (aCorr) Functions

Although aCorr is a special case of xCorr in which Y is equal to X, they are used for different purposes. While xCorr is used to reveal correlation between two different signals, aCorr is used to detect non-randomness in a signal.

xCorr of a discrete time series X and Y (with N=4500) is computed as:

$$R_{xy}(m) = \begin{cases} \sum_{n=0}^{4500-m-1} X_{n+m}Y_n & \text{if } m \geq 0 \\ R_{xy}(-m) & \text{if } m < 0 \end{cases} \tag{4.6}$$

MATLAB gives the correlation array as:

$$c(k) = R_{xy}(k - 4500), k = 1, 2, ..., 2N - 1 \tag{4.7}$$

Autocorrelation function can be obtained using $X_{n+m}.X_n$ instead of $X_{n+m}.Y_n$.

4.3 Frequency Domain Analysis

Analysis in frequency domain gives opportunity to see how much of power is presented at each frequency. Thus, it is important to understand the dynamics of the body sway and the strategies used by subjects.

4.3.1 Fast Fourier Transform (FFT)

FFT is used to transform a signal (often in time domain) to the frequency domain or vice versa. In order to apply FFT to a time series of length N, the Discrete Fourier Transformation (DFT) is used. After the transformation, it gives another series of length N with complex coefficients. These coefficients were calculated by MATLAB through the Equation 4.8.

$$Y(k) = \sum_{n=1}^{N} X(n).e^{-i(\frac{2\pi(n-1)(k-1)}{N})} \tag{4.8}$$

A representative plot for FFT of a CoPx signal was given in Figure 4.3.

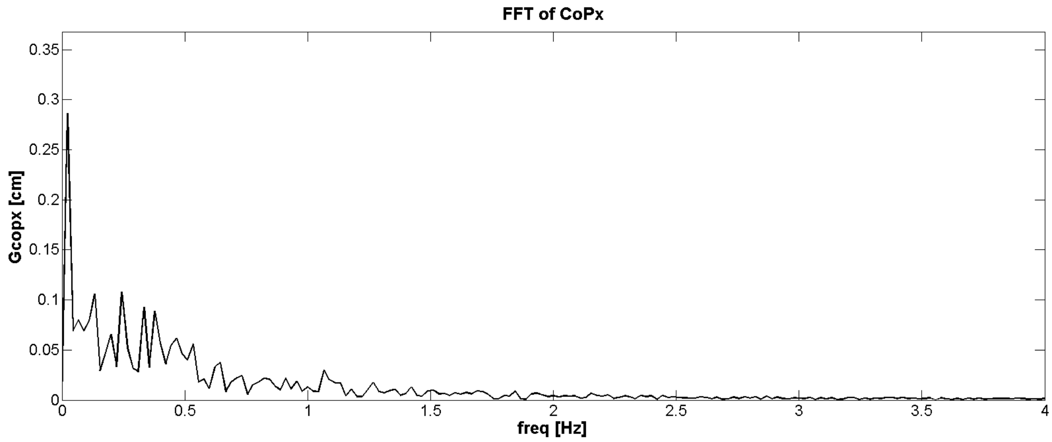

Figure 4.3: A Sample Plot for FFT of a CoPx

4.3.2 Power Spectral Density (PSD)

PSD estimates were calculated to assess the distribution of the power of CoP signals in frequency domain. They were computed from FFT of the autocorrelation of the CoP signals [50]. PSD estimates were plotted with respect to frequency. Since the data collection duration was 45 seconds, the maximum resolution (Δf) in these plots were $\frac{1}{45}$ Hz. Besides, some other metrics were computed over the PSD estimates. Power Spectral Density estimate as a function of frequency is obtained through the equation:

$$G_x(f) = 2\int_{-\infty}^{\infty} R_{xx}(\tau)e^{-i2\pi f\tau}d\tau \tag{4.9}$$

where τ is the delay operator and R_{xx} is the autocorrelation function explained in Section 4.2.3.

4.3.3 Area under the PSD (AuPSD)

Body sway is a non-linear dynamics and control of this dynamics have not been known yet. Frequency characteristics have also not been known. There may be adjacent frequencies which correspond to the same event. In order to reveal whether there are events occurred with consecutive frequencies, each PSD estimate plots were analyzed segmentally. In addition, two types of AuPSD, absolute and relative, were computed for the sake of easiness of results comparison. Comparison of AuPSD is not easy between patients and healthy subjects without using relative AuPSD because of the scale problems. Integration segment width was chosen as $4\Delta f = \frac{4}{45}$ for relative and absolute AuPSD. For the total AuPSD, segment width was chosen $\Delta f = \frac{1}{45}$.

Total area under the PSD estimate plot is obtained with the formula given in Equation 4.10.

$$TotalAuPSD = \sum_{i=1}^{f_{limit=360}} \frac{G_x(i) + G_x(i+1)}{2}.\Delta f \qquad (4.10)$$

4.3.3.1 Absolute AuPSD

Absolute AuPSD was computed as:

$$AbsoluteAuPSD(i) = \sum_{j=41-3}^{4i} \frac{G_x(j) + G_x(j+1)}{2}.\Delta f, i = 1...f_{limit} \qquad (4.11)$$

where G_x is PSD estimate function and Δf is the width of the frequency segment ($\frac{1}{45}$) in Hz. Here, f_{limit} was also chosen as 90 for the limitation of output data between 0-8 Hz since it is assumed that there is no postural dynamics beyond 8 Hz. Each integration segment of absolute AuPSD corresponded to sum of 4 adjacent areas separated by 5 frequency steps of $\frac{1}{45}$ Hz. AuPSD series were plotted with respect to frequency which is mid-point of the 5 frequency steps. (Hz).

Magmax For all trials, absolute AuPSD plots were analyzed to find the maximum magnitude value. These points were named as **magmax** (maximum magnitude) which gives information about the power of the dominant frequency of postural sway.

Fmagmax This metric is the corresponding frequency to the magmax. It was named as **fmagmax** (frequency of magmax) which shows the dominant frequency around which frequencies included in postural sway concentrates.

4.3.3.2 Relative AuPSD

Relative AuPSD was obtained from division Absolute AuPSD to total area. It was calculated through the Equation 4.12.

$$RelativeAuPSD(i) = \frac{AbsoluteAuPSD(i)}{TotalAuPSD} \tag{4.12}$$

Absolute and relative AuPSD plots with respect to mean frequency were given in Appendix B.

4.3.4 Spectral Moments

Spectral moments $\mu(k)$ were computed for k= 0, 1, 2 through the Equation 4.13.

$$\mu_k = \sum_{i=1}^{m} (i * \Delta f)^k . G_x(i * \Delta f) \tag{4.13}$$

When k is zero, Equation 4.13 gives the total area of the power spectrum, total power.

$$\mu_0 = Power = \sum_{i=1}^{m} G_x(i * \Delta f) \tag{4.14}$$

4.3.5 Modified Centroidal frequency (CFREQ)

Centroidal frequency is defined as the frequency at which the spectral mass is concentrated. It is also referred to as the zero crossing frequency, or mean rate of zero crossing. It is computed using zeroth and first spectral moments as shown in Equation 4.15. Its unit is in Hz [50]. Originally, this metric is calculated over second order spectral moment instead of first order. However, since it did not work well in between 0-1 Hz, it was calculated over first order spectral moment.

$$CFREQ = \frac{\mu_1}{\mu_0} \tag{4.15}$$

4.3.6 Frequency dispersion (FREQD)

FREQD is a unitless metric of the variability in the frequency content of the power spectral density. The frequency dispersion is zero for a pure sinusoid and increases with spectral bandwidth to a maximum of one [50].

$$FREQD = \sqrt{1 - \frac{\mu_1^2}{\mu_0 \mu_2}} \tag{4.16}$$

More detailed explanation and some comparative applications were given in the appendix D.

4.4 Statistical Analysis (Analysis of Variance)

Analysis of Variance (ANOVA) is a powerful statistical tool for splitting the aggregate variability found inside a data set which includes more than two samples. In this study, repeated measure 3-way ANOVA with a significance level of 0.05 was conducted to compare independent variables, namely health conditions (patients vs. healthy subjects), eyes conditions (EO vs. EC), support surfaces (RS vs. CS). Metrics included in statistical analysis are PL, Variance, CFREQ, FREQD and fmagmax. Since the repetition of trials caused some undesired effects due to adaptation (learning) of subjects to the surface and task, repeated measurements (second and third) on CS trials were not included in the statistical analysis.

CHAPTER 5

RESULTS

In this chapter, results of statistical analysis and results obtained from CoPx and AuPSD plots by observation were given. All results were examined to reveal the effect of sensory inputs such as eyes, vestibular and tactile. Besides, frequency domain analysis were examined to understand how the changes in sensorimotor components affected the dynamics of the CoPx.

5.1 Statistical Analysis (ANOVA) Results

There are two metrics in time domain and three in frequency domain. These metrics mainly were used to compare BVL patients and healthy subjects and of course the other sensory conditions. For the statistical analysis, MATLAB® and IBM SPSS Statistics® software's have been used.

5.1.1 Results for Path Length

Path length is a metric to see total movement travel in horizontal plane (both antero-posterior and mediolateral) in time domain. It is also only metric that was calculated using both CoPx and CoPy, not only CoPx. Statistical analysis showed that BVL patients travelled significantly longer path than healthy subjects did ($p=0.0175$) (See Table 5.1a). In addition, all subjects had longer path length values in EC conditions when compared with EO conditions ($p=0.0133$) (See Table 5.1b).

Table 5.1: Descriptive Statistics for Path Length

Subject	Mean	Std. Dev.	Eyes	Mean	Std. Dev.	Subject	Mean	Std. Dev.
BVL	109,553	48,886	**EC**	110,057	47,983	**BVL**	128,306	61,754
HS	87,486	13,858	**EO**	86,982	15,998	**HS**	91,807	15,843
Total	98,519	37,302	**Total**	98,519	37,302	**Total**	110,057	47,983
1a			**1b**			**1c - in EC condition**		

Another important result was that closing the eyes was a distinctive condition for BVL patients (p=0.042) (See Table 5.1c). This may be important to explain the compensation of the BVL's after their acute stage.

Next four metrics were calculated over the CoPx, since the quiet stance geometry is different with respect to the two-axers and is more stable in y-axis (like a four-bar-linkage) than x-axis (like an inverted pendulum), which (comparison of the two-dynamics) is not in the scope of this thesis.

5.1.2 Results for Variance

Variance metric gives information about how the time series of CoPx deviates its mean. In this study, since the CoPx signals were detrended, means were equal to zero. Thus, variance shows the deviation from the origin.

Statistical analysis for variance metric did not give any significant result. However, it is not a striking outcome for this study. It was discussed in the next chapter.

Next three metrics were obtained from frequency domain analysis.

5.1.3 Results for Fmagmax

Fmagmax is the frequency value at which the power of the sway dynamics reaches the highest value. This may be thought as a dominant frequency which drives the dynamics. Thus, it is important to reveal the change in the characteristics of the sway dynamics.

ANOVA results show that the dominant frequency of BVL's is higher than healthy subjects' (p=0.0288) (See Table 5.2a). This means that BVL's lost their low frequency sway characteristics, that is, dominant frequency of BVL's shifted to right in the frequency spectrum.

Moreover, at the trials performed on the compliant surface, fmagmax values of BVL patients' were significantly higher than healthy subjects independently of eyes condition (p=0.038) (See Table 5.2b).

Table 5.2: Descriptive Statistics for fmagmax

Subject	**Mean**	**Std. Dev.**	**Subject**	**Mean**	**Std. Dev.**
BVL	0,2254	0,3026	**BVL**	0,3111	0,3945
HS	0,0889	0,1148	**HS**	0,0762	0,0826
Total	0,1571	0,2370	**Total**	0,1937	0,3041
2a			**2b - in CS condition**		

5.1.4 Results for CFREQ

CFREQ is a similar metric to fmagmax. While fmagmax give information about the dominant frequency, CFREQ shows the mean frequency roughly. It may be thought as the center of frequency in frequency spectrum. Thus, it is another independent metric to show that the body sway frequency of BVL patients' shifted to higher frequencies compared to healthy subjects' (p=0.0112) (See Table 5.3). In contrast, there is no significancy between the eyes conditions. However, it may be a meaningful outcome such as that it has been discussed in next chapter.

Table 5.3: Descriptive Statistics for CFREQ

Subject	**Mean**	**Std. Dev.**
BVL	0,4301	0,2719
HS	0,2791	0,1200
Total	0,3546	0,2218

5.1.5 Results for FREQD

FREQD metric may be thought as a simple measure for complexity of a signal because it gives information about how many types of frequency are included in the signal. Thus, it is the most important metric to test the hypothesis of this study. According to the hypothesis, since the number of information channels decreased due to the fact that BVL patient lost their one of the sensory organ, their sway characteristics would change. This may mean that the complexity of the dynamics (physiologically correlated sensory-motor dynamics) would decrease (in other words, entropy would increase). This analysis may be thought as an introduction for the thermodynamical approach to the erected posture.

Statistical analysis for FREQD showed that the complexity of signals of BVL patient' was dramatically lower (loosing their long-term correlations, see Appendix D as well; also re-considered with the PSD estimates having shown that power spectrum has shifted to the right) than healthy subjects' (p=0.0004) (See Table 5.4a). BVL patients and healthy subjects also have significantly different complexity values in the CS independently of eyes conditions (p=0.017) (See Table 5.4b).

On the other hand, eye conditions were another distinctive factor affecting the complexity of the signals (p=0.0013) (See Table 5.4c). In addition, in the EC condition, healthy subjects showed more complex sway dynamics than BVL patients' did (p=0.003) (See Table 5.4d).

Table 5.4: Descriptive Statistics for FREQD

Subject	**Mean**	**Std. Dev.**	**Subject**	**Mean**	**Std. Dev.**
BVL	0,8783	0,1014	**BVL**	0,8783	0,1014
HS	0,9478	0,0380	**HS**	0,9478	0,0380
Total	0,9130	0,0835	**Total**	0,9130	0,0835
4a			**4b**		
Subject	**Mean**	**Std. Dev.**	**Subject**	**Mean**	**Std. Dev.**
BVL	0,8532	0,1138	**BVL**	0,8317	0,1049
HS	0,9363	0,0425	**HS**	0,9315	0,0406
Total	0,8947	0,0944	**Total**	0,8816	0,0932
4c – in CS condition			**4d – in EC condition**		

5.2 Observational Results through CoPx and AuPSD Plots

Although plotting the data does not give a quantitative result but it is very useful way to visualize the data. The data actually contains more information than the amount we obtain from it by the help of quantitative metrics. Hence, interpreting the data through plots may give some additional information. In this study, CoPx (for time domain) and AuPSD (for frequency domain) plots of subjects were examined due to this reason. However, note that these results were only depended on observation.

5.2.1 Results through CoPx Plots

CoPx shows the subjects behavior during the trial in anteroposterior axis. For the CoPx plots, the most striking result is that the low frequency base line activity observed in the results of healthy subjects (long-term correlations) does not exist in the results of BVL's. Two representative plots (one HS's plot and one BVL's plot) were given in Figure 5.1 and Figure 5.2, respectively. CoPx time series signal may be assumed as a sum of many signals with different frequencies but BVL patients lost their low frequency body sway in this signals due to their disease. After BVL subjects had lost their low frequency activity, they showed different CoPx patterns from each other BVL's.

Moreover, in EC condition, high-frequency body sways were acted by all subjects compared with EO condition in general. However, BVL subjects reached higher frequency than HS.

Another frequently obtained result was amplitude of CoPx increased in CS conditions compared to RS condition. On the other hand, decrease of amplitudes were seen in the repeated trials on CS. These decreases were also confirmed by the PL and Variance metrics. Due to this adaptive behavior to the CS, repeated trials were not added to the statistical analysis. Only the first trial of each CS set was used for ANOVA. CoPx plots of all subjects were attached to thesis in Appendix A.

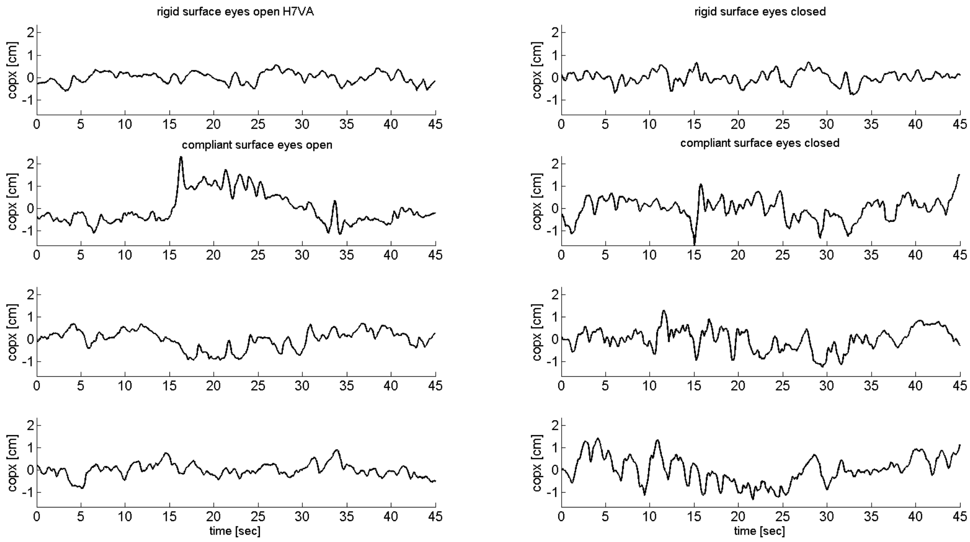

Figure 5.1: CoPx signals of a representative healthy subject (H7VA)

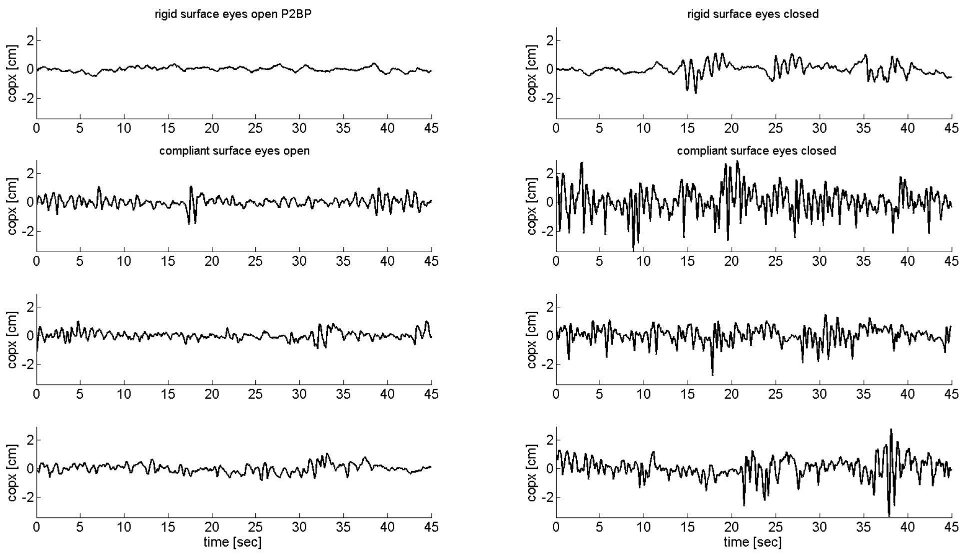

Figure 5.2: CoPx signals of a representative BVL subject (P2BP)

5.2.2 Results through AuPSD Plots

AuPSD plots gives idea about dissipated power corresponding to frequency spectra of body sway. These plots showed that BVL subjects lost low-frequency components within their postural sways in EC condition. In addition, their power spectra were spread out on larger frequency ranges. In contrast, in same condition, relative AuPSD plots of HS showed that the peak power percentage corresponding to frequency segments placed at the first segment. In addition to that their power spectra did not spread out. On the contrary, it densed around the smallest frequency segment. Additionally, spectral range widened in the first CS trial for all subjects.

Although there is no obvious difference between HS and BVL in EO & RS condition, the peak frequency for HS was at the smallest frequency segment in EO & CS condition while power spectra has spread out on a wider range for BVL patients. Moreover, BVL's increased the power transfer from high-frequency zone to low-frequency zone with repeated trials of EO condition. It is not possible to say the same thing for trials in EC condition. AuPSD plots of all subjects were attached to thesis in Appendix B.

CHAPTER 6

DISCUSSION & CONCLUSION

In this part, results presented in the previous chapter were compared and discussed with the literature given in the introduction chapter.

6.1 Discussion

Firstly, both healthy and BVL subjects could somehow success to maintain their upright posture without help even in EC conditions. This shows that postural control is plastic and driven by the cooperation of senses, not mainly relying to only one of them. Even though some sensory information are missing, human nervous system can overcome this strait by replacing/reweighting sensory inputs as *Peterka* mentioned [24]. However, this study demonstrated that lack of vestibular information causes change in postural sway characteristics. In this thesis, these changes were tried to be revealed through some metrics.

One of important outcome is that metrics in time and frequency domain could distinguish between healthy and BVL subjects except variance metric. For example, pathlength revealed that BVLs traveled in a longer path compared to HS. In addition, EC is a distinctive condition for only BVL. These may be interpreted as BVLs compensated to some extent for their disease using their eyes more than they had in the past. However, they may not have a stable balance as healthy people due to vestibular loss because it is expected that vestibular loss changes postural responses and strategies [42]. Besides, results of pathlength analyses are not enough alone to evaluate postural stability because all oscillations may not be malign (bad variance, local instabilities; fall-like behaviour) movement. On the contrary, they may be benign oscillations (good variance -benign manifold-, search behaviour) as mentioned in the introduction part. The "meaning" of the manifolds should be interpreted with respect to the interaction in-between the "self" and the environment as introduced in Introduction (long-term correlations causing highly nonlinear dynamics versus short term high frequencies at comparatively uncorrelated but higher entropic dynamics) [51] [52] [53] [54].

Variance (being the "whole" area under the PSD diagram), the other time domain metric, did not give any significant result (because, rather should be decomposed to "good" and "bad" manifolds). However, if BVLs had performed experiments in acute period of their disease, variance might have been a distinctive metric for patients because adaptation to disease may have caused to decrease in variance.

Actually, the main metrics to test hypothesis were in frequency domain because the most important expectations were about postural control characteristics. Fmagmax results showed that frequency value with maximum power of BVLs shifted to higher values. This shift was also shown with CFREQ metric. These two metrics clearly revealed that BVLs oscillated with higher frequencies than HS' and BVLs' dominant sway frequencies were higher than HS'.

The most important results to support main hypothesis were obtained through FREQD metric. According to hypothesis, it was expected that lack of vestibular information would lead to disappearance in some postural dynamics (uncorrelated dynamics). For example, if CoPx is assumed as a sum of many functions, then low-frequency functions involved in CoPx will tend to make FREQD value bigger (higher the FREQD value larger the long-term correlations are, see Appendix D) while (uncorrelated) high-frequency functions do it smaller (much more entropic). Thus, the average FREQD value of BVL subjects will be smaller (expected to be more entropic) than healthy subjects' if BVL's loses their low-frequency dynamics [55] [56] [57]. As a result, FREQD metric illustrated that BVLs lost their low-frequency dynamics with smaller FREQD. Moreover, observational results supports the missing low-frequency activity in BVLs.

Low-frequency activity loss in BVLs may be interpreted as BVLs do not perform search behavior (loss of long-term correlations "may be" concomitantly weighting for balance metrics). This behavior is an inherent dynamics which arises when the necessary sensory inputs are included into sensorimotor integration. It is expected that loss of vestibular input cause to deficiency in perception. They cannot perceive clearly their body-sway. This is because they cannot distinguish between self- and external-perturbation. Most BVLs say that in some cases they feel a “sense of space”. This sense may be the definition of the lack of vestibular information in conscious level.

The lost inherent low-frequency activity may be a search (like an adaptive nonlinear control) behavior. It probably arises as a result of all experiences on postural activities. This inherent dynamics is started to build in infancy, then it is developed in time. Postural strategies, postural responses or even posture are not mentioned in infancy so reflexes are more dominant at that period. Kandel suggests a model with at least three level for motor system. This model is shown in Figure 6.1 [29], schematically. First level, spinal cord, is responsible for the reflexes. Second level consists of brain stem, cerebellum and basal ganglia. This level is responsible for sensory fusion, and automatic postural response both of which are in the scope of this thesis. The last level, cortex, is responsible for the voluntary and conscious actions. In this study, interviews with subject showed that QS trials were ordinary and simple tasks for HSs. They did not make an extra effort to stand in balance. Even one subject told that she planned her schedule for the evening meal during the trials. This shows that these people do not need to do conscious actions to balance in QS. Probably, the posture control in QS is governed by lower levels. On the other hand, BVLs had to direct their attention to task in the experiment, since stability of their posture probably has not been controlled by only an inherent dynamics. They need to do conscious corrections because they probably compensate for the lack of "informative-habitual/adapted" (correlated) (which is no more a search) behavior in this way.

Furthermore, the complexity of the multiple level motor system model shown in Figure 6.1 supports the idea that posture control cannot be modeled with a classical control method. Since the posture control is a non-linear control system, all inner loops, sensor thresholds and the self-reference of the system should be taken into consideration when modeling [58].

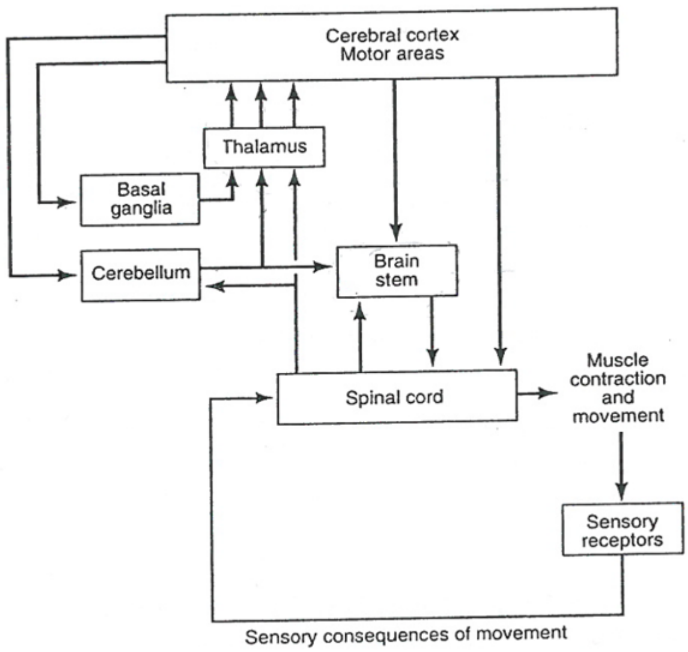

Figure 6.1: Diagram for motor system levels and interaction between these levels

Moreover, eye conditions were not found as a significant variable for most of metrics. It was already known that after voluntary actions nervous system prepared itself for the consequences of this action by the help of efferent copy [23]. FREQD is also significant to distinguish BVLs and HS in CS and in EC conditions, separately. This may be due to the fact that BVLs reweighted their senses. The BVL patients develop a dependency to visual and somatosensory information (wiring the correlation in-between as it is the sensory configuration that is most exposed/habituated or likely to be the most "exploited") during their diseases [59].

The effect of CS was tentative for all subjects but note that compliant surface trials do not provide to test subjects with somatosensory loss. It may only be thought as a reduction/ıncluding noise on tactile information.

Another important result is that BVLs and HSs could not be distinguished in EO&RS condition. This means that patients have adapted to stand in rigid surface when their eyes open. EO&RS is the condition that they are most experienced to in daily life so it is the condition in which they are more "successful". They already "do not need to search" environment again. However, if at least one of the test conditions is changed with some provocation (EC, CS, tilt, etc.), then the balance difference between BVLs and HS will be observed. BVLs are not good at characterizing new test conditions while HS are. Adaptation of BVLs to EO&RS is not a universal solution since BVLs cannot come up with a new postural situation. It is known that coping with a postural (motor) task requires to be aware of characteristics of the task. These characteristics are of both actuator (body/self) and environment (external) such as gravitational force, support surface or self-body movements etc. This means that solving a postural (motor) task is also closely related with the concept of self-perception. If one cannot distinguish self-body movements from the movements due to external factors, he/she will not perceive the actor in the action. This demonstrates that all sensory information needed for creating self-perception is also crucial for solving a motor control problem. As a result, missing low-frequency activity in BVLs seems to have caused loss of "information"/rather is an exploitation needed for postural adaptation to changing conditions [59]. This low-frequency dynamics may be providing information (in the sense of long-term correlations) about the one's postural situation. Thus, it may be called "benign" behavior (a good variance manifold).

On the other hand, loss of vestibular input does not mean that BVLs will no longer maintain their balance. Experiments illustrates that BVLs achieved to balance by the help of remaining senses. They develop some kinds of dependencies on vision and touch. This dependency was found to vary in each patient [22] [13]. Therefore, there is no common CoPx pattern for BVLs. In order to perceive their postural situations, patients need to stimulate and activate their other senses to use together with proprioceptive (self) information. For example, if a patients developed a touch dependency, he/she needs to do active search behavior with his/her foot. Unfortunately, in this study, there was no opportunity to make electromyography (EMG) measurement to reveal that patients do active movement. Thus, it can be said that a patient trying to actively use the touch senses of his/her based only on patients own statements. The CoPx plots of a BVL patient who declares that he/she did active touch was given in Figure 6.2. In addition, CoPx signals of patients with two different types of CoPx pattern were also given in Figure 6.3 and Figure 6.4.

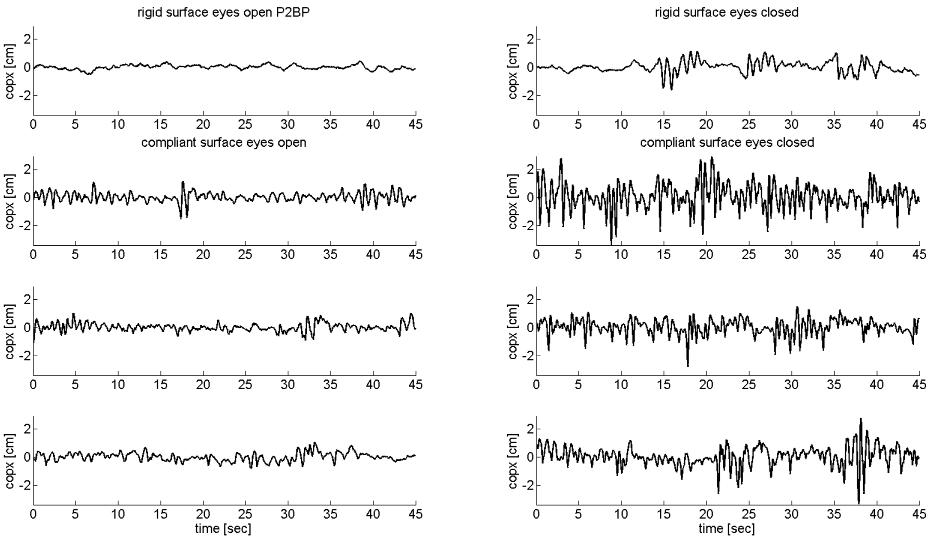

Figure 6.2: CoPx Plots of BVL2BP on RS vs. CS and EO vs. EC conditions

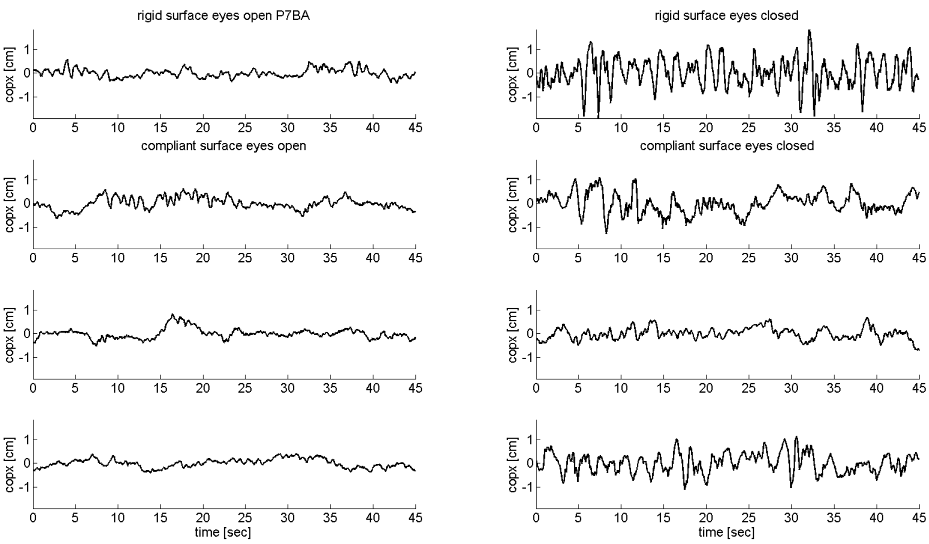

Figure 6.4: CoPx Plots of BVL7BA on RS vs. CS and EO vs. EC conditions

Moreover, another important result to support the idea that BVLs develop different adaptation to their diseases was obtained through the analysis of the area of the 95% confidence ellipses. In this analysis, means and standard deviations of confidence ellipses were calculated. These values were given in Table 6.1.

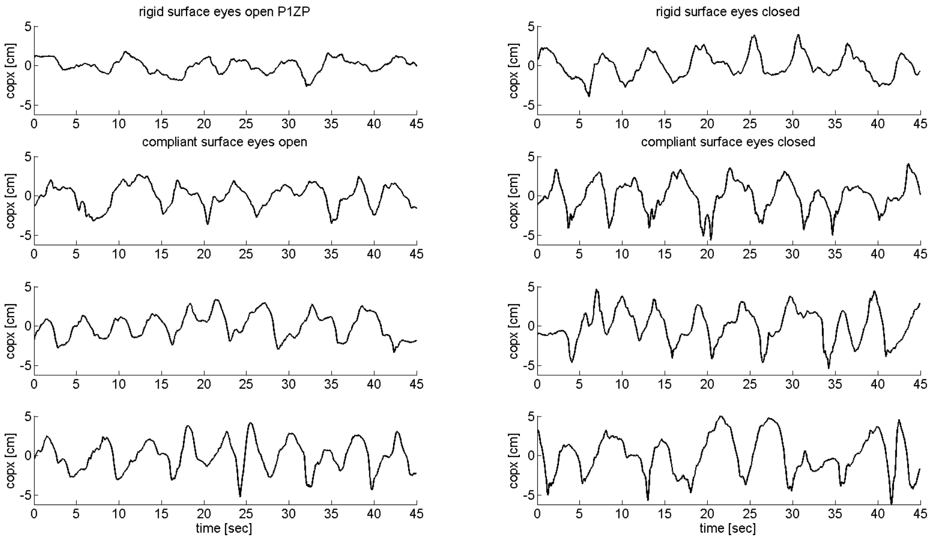

Figure 6.3: CoPx Plots of BVL1ZP on RS vs. CS and EO vs. EC conditions

Table 6.1: Areas of the 95% confidence ellipses for first EO and EC trials in EO and EC conditions and their means and standard deviations

	Healthy Subjects				**BVL Subjects**				
	RS		**CS**		**RS**		**CS**		
Subject Code	**EO**	**EC**	**EO**	**EC**	**EO**	**EC**	**EO**	**EC**	**Subject Code**
HS1AK	0.0886	0.0993	0.4473	1.3855	7.2365	48.2925	149.2645	240.3630	BVL1ZP
HS2CC	0.0269	0.0919	0.1891	0.5023	0.0125	0.2918	0.3144	0.9531	BVL2BP
HS3SS	0.0129	0.0059	0.0175	0.0166	0.2866	0.2458	0.1213	0.6395	BVL3HS
HS4OG	0.0055	0.0159	0.0292	0.0378	0.0417	0.0346	0.0652	0.1425	BVL4HK
HS5YY	0.1057	0.3440	0.8066	2.0390	0.5928	0.3691	1.3973	0.9842	BVL5DI
HS6ES	0.1585	0.2153	0.1920	2.5352	0.0186	5.5396	0.1843	20.5731	BVL6AM
HS7VA	0.0797	0.3503	0.0636	0.6696	0.0245	0.0458	0.5837	0.1070	BVL7BA
Mean (mm^2)	0.0683	0.1604	0.2493	1.0266	1.1733	7.8313	21.7044	37.6803	
Std. Dev. (mm^2)	0.0518	0.1341	0.2655	0.9126	2.4833	16.6211	52.0779	83.0329	

Table 6.1 illustrates that BVLs did not have a common adaptation because areas of their confidence ellipses have a large variation while HSs' have not. This means that sway characteristics of HS was similar with each other but BVLs used different strategies in different surface and eyes conditions due to different adaptation. For example, most of the HSs were affected in CS&EO condition more than those in RS&EC condition. Also, confidence ellipse areas in these two condition were very close for most of the HSs. However, these area values were found dramatically scattered for BVLs. Therefore, it is interpreted that BVLs developed different adaptation to their diseases so different test conditions influenced them in different ways. To this end, it would be very helpful if the clinical and laboratory evaluation of the BVL subjects had been

somehow included/considered in the analyses.

In this study, it was assumed that trial performed in EO&RS is a default condition for all subjects and do not affects naivete of subjects. Thus, this condition measured at first and has not been shuffled with EC&RS. It was also assumed that testing in EO&RS condition does not affect the measurement in EC&RS condition.

Finally, note that CoPx is a result of the postural responses. Postural responses are also results of the sensorimotor integrations. If it is asked to reveal the causality between sensorimotor integration and postural responses, the EMG measurements over the posture muscles (actuators) should be made(especially as an estimation of the "self" through proprioception; i.e., muscle spindle activation). Otherwise, interpreting the data will be difficult and ambiguous.

6.2 Conclusion

In this study, the contribution of the vestibular system to postural control was examined comparing the CoPx signals of BVL and healthy subjects measured in different eye and surface conditions. Then, results were tried to be discussed from an ecological and a philosophical perspectives.

Such studies are important for not only to understand the mechanism of the posture control but also to develop new methods for diagnosis and rehabilitation of patients with balance disorder. Thus, replication of such studies is necessary.

To conclude, results demonstrates that BVLs lack of low-frequency CoPx activity (long-term correlated nonlinear dynamics). Instead of this, they oscillate with a higher-frequency movement caused by rapid postural corrections (searching with an increased amount of entropi). This change in postural responses was interpreted as BVLs lost their source of "information" (author is rather close to see it as an adapted/-exploited behaviour rather than an active search for information; given that information accompanies to entropy) due to loss of vestibular input. The concept of acquiring information from the action was underlined specifically. With ecological view, human motor control system cannot be approached as a classical mechanical control system.

In a mechanical system, the most "desirable" state is when the system is perfectly stationary/stable. On the other hand, for human motor control system, same state corresponds to "*no perception*, i.e. "*no information*" and minimum entropy. Thus, if we have to answer the question asked in the opening, the answer will be "*information comes from the action*".

Finally, "*in the beginning was **the Deed.***"

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APPENDIX A

COPX PLOTS OF SUBJECTS

A.1 CoPx Plots of Healthy Subjects

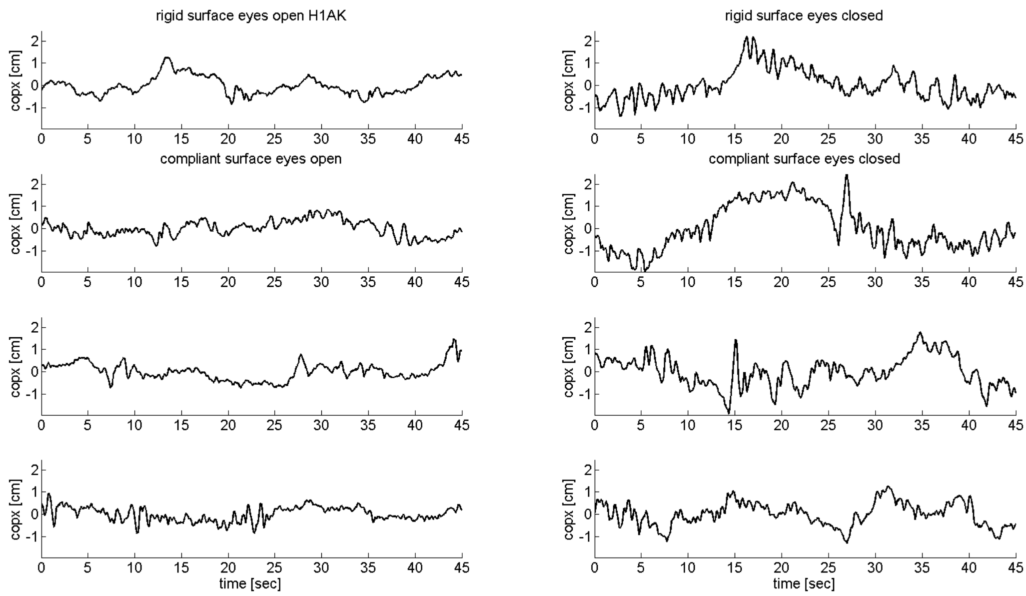

Figure A.1: CoPx Plots of HS1AK on RS vs. CS and EO vs. EC conditions

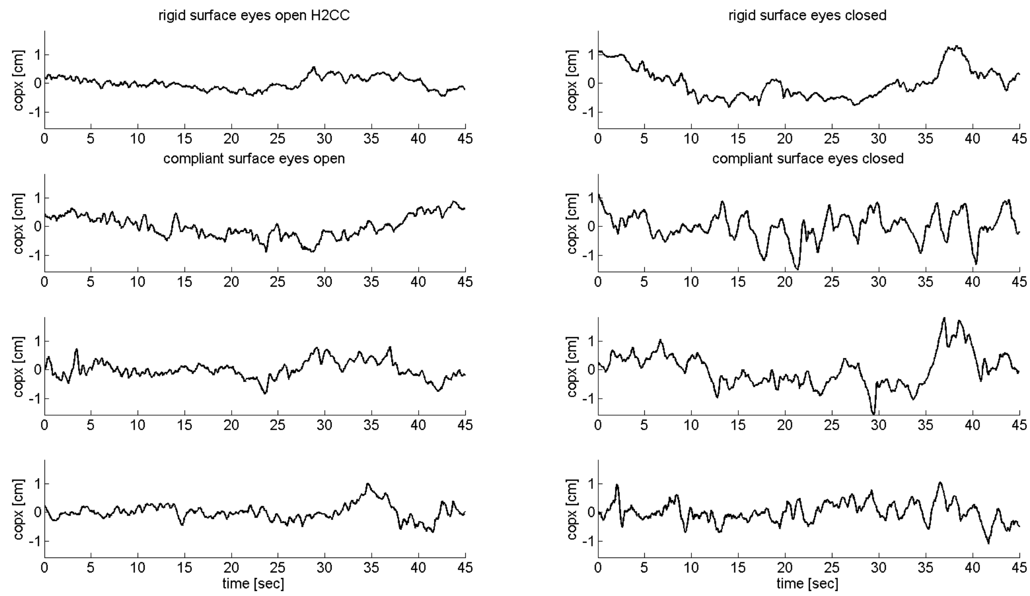

Figure A.2: CoPx Plots of HS2CC on RS vs. CS and EO vs. EC conditions

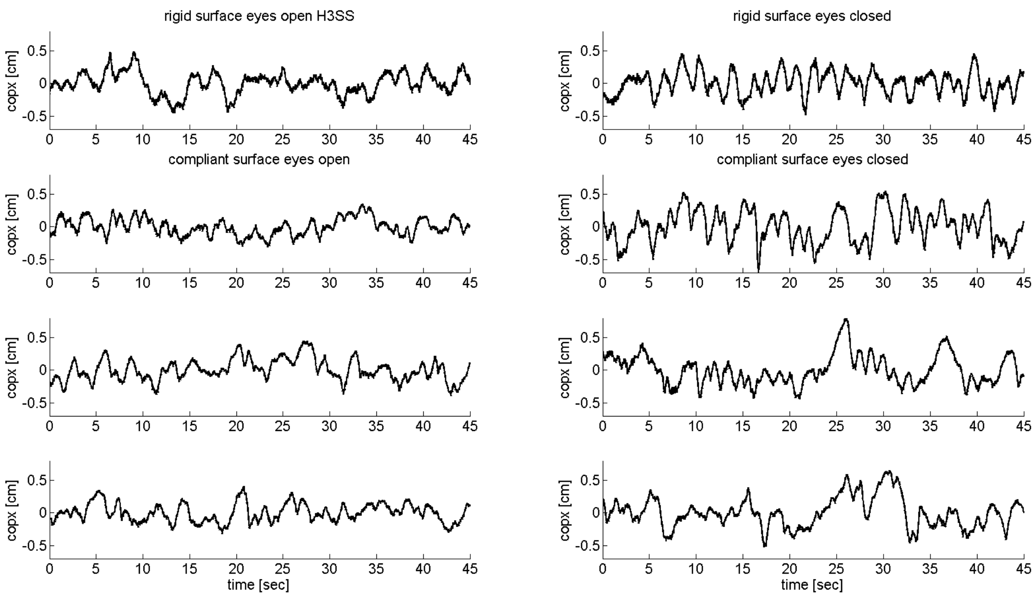

Figure A.3: CoPx Plots of HS3SS on RS vs. CS and EO vs. EC conditions

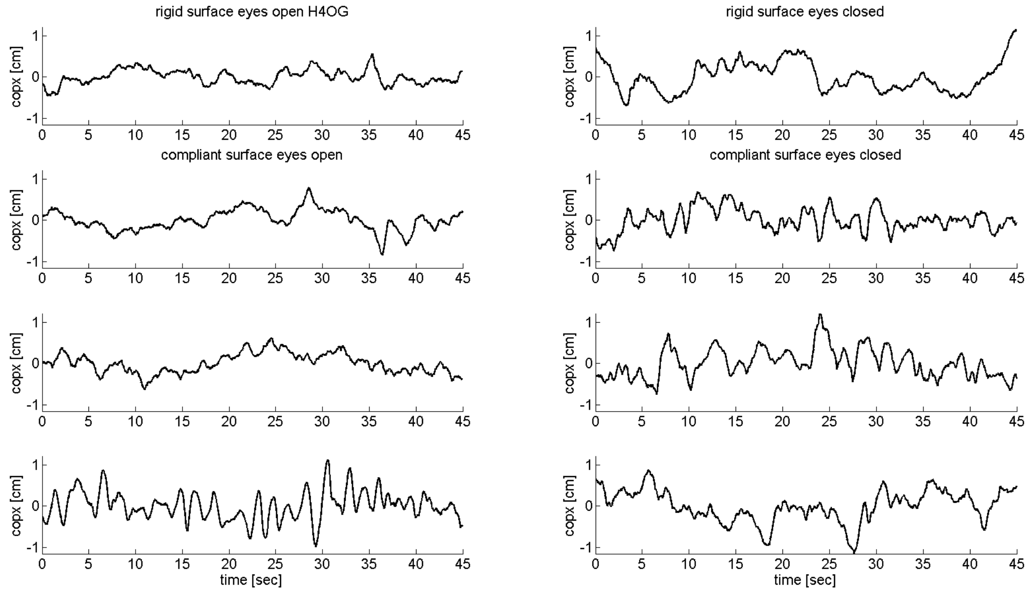

Figure A.4: CoPx Plots of HS4OG on RS vs. CS and EO vs. EC conditions

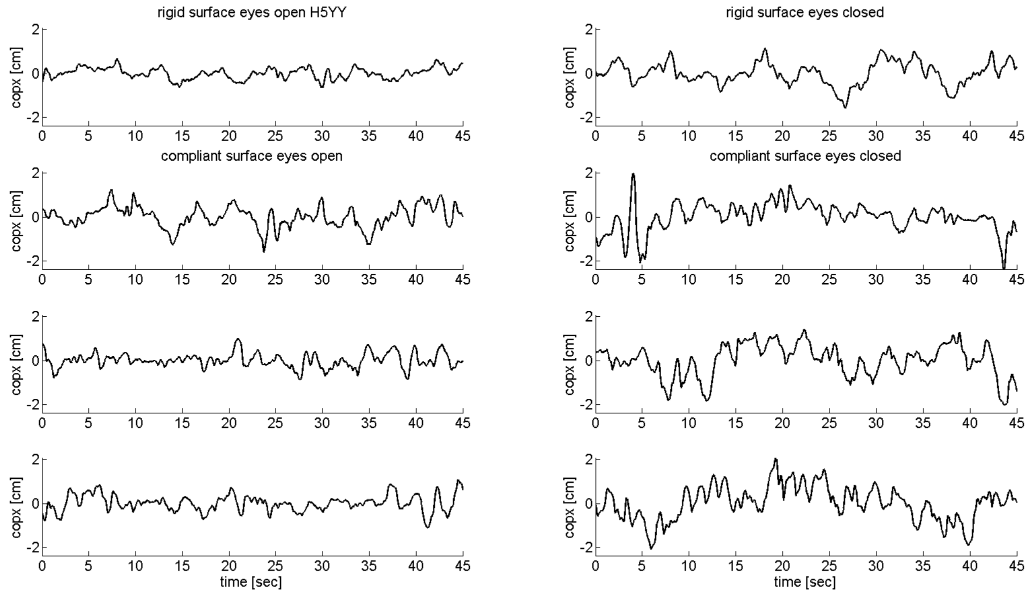

Figure A.5: CoPx Plots of HS5YY on RS vs. CS and EO vs. EC conditions

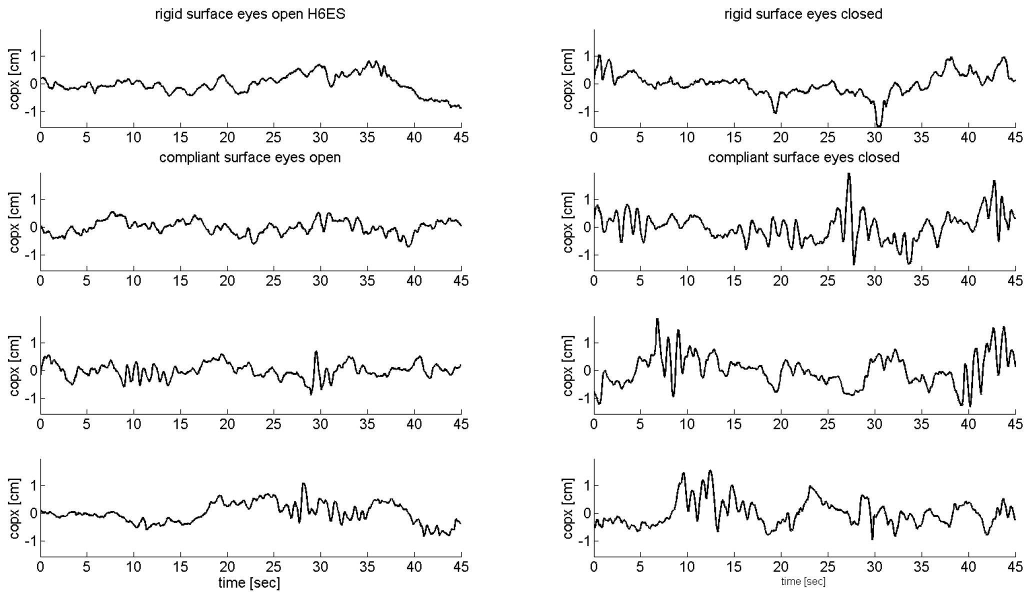

Figure A.6: CoPx Plots of HS6ES on RS vs. CS and EO vs. EC conditions

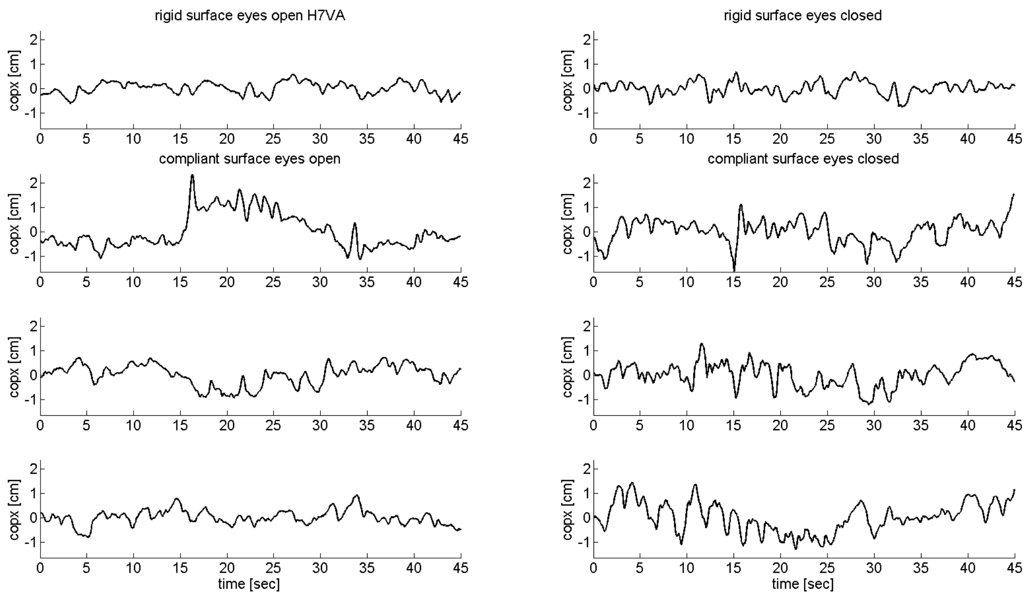

Figure A.7: CoPx Plots of HS7VA on RS vs. CS and EO vs. EC conditions

A.2 CoPx Plots of BVL Subjects

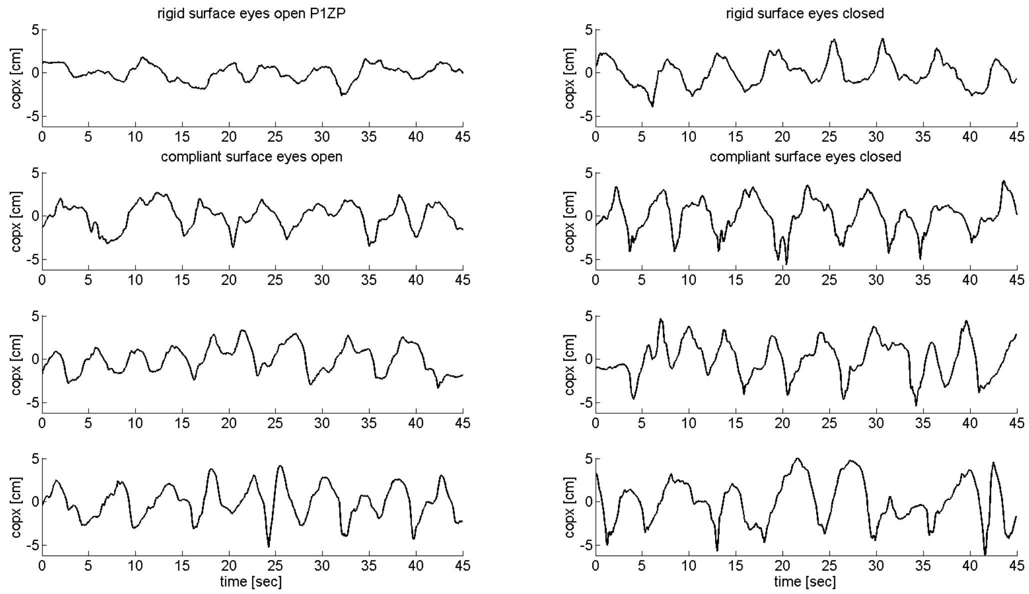

Figure A.8: CoPx Plots of BVL1ZP on RS vs. CS and EO vs. EC conditions

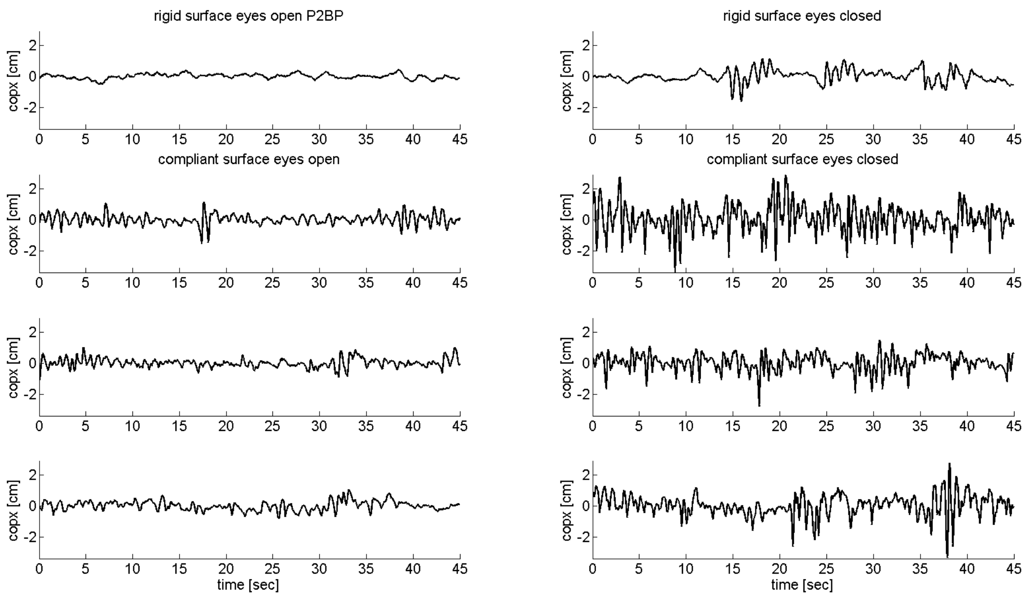

Figure A.9: CoPx Plots of BVL2BP on RS vs. CS and EO vs. EC conditions

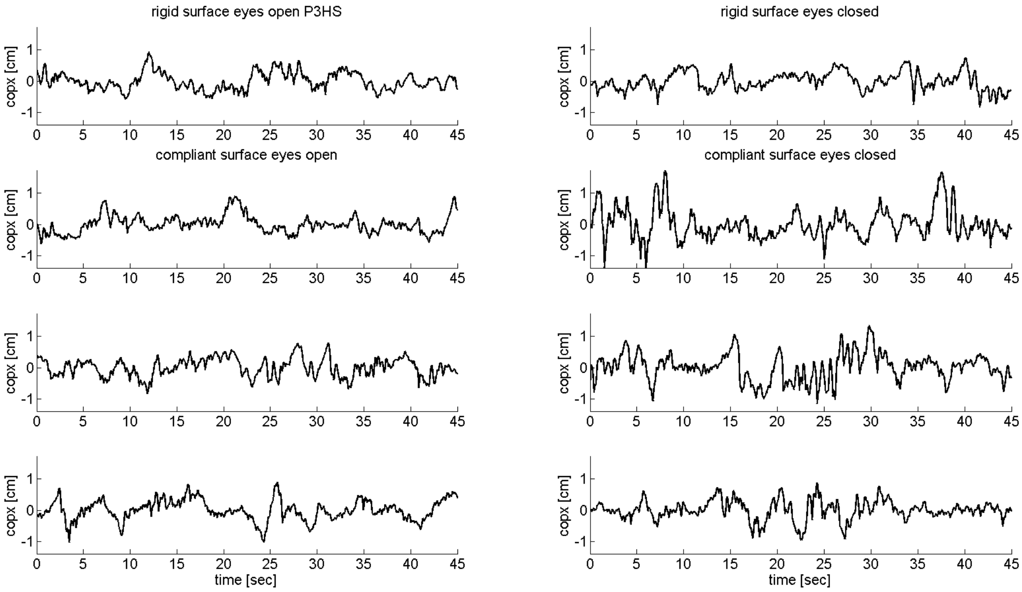

Figure A.10: CoPx Plots of BVL3HS on RS vs. CS and EO vs. EC conditions

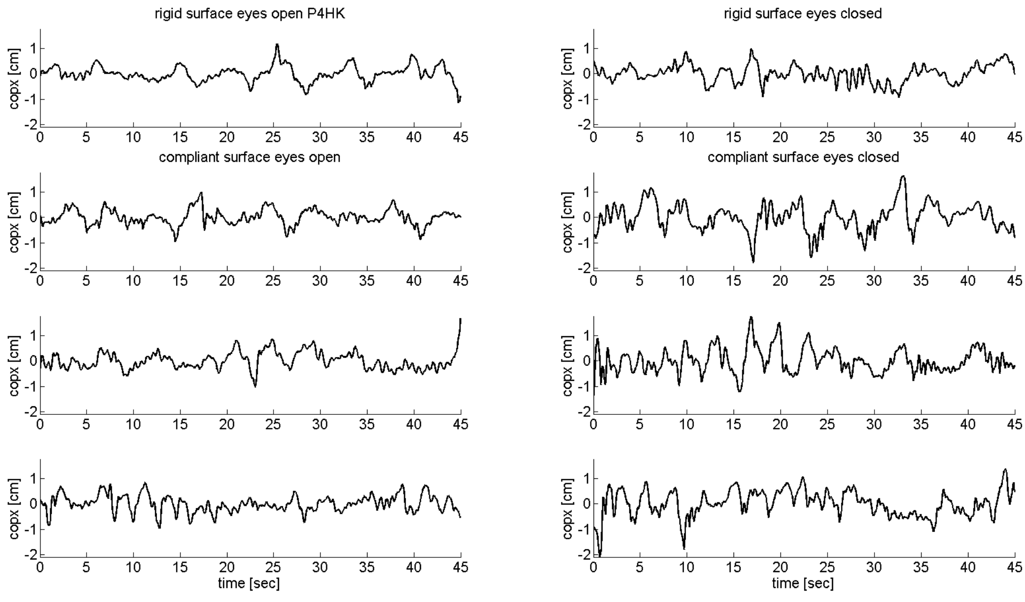

Figure A.11: CoPx Plots of BVL4HK on RS vs. CS and EO vs. EC conditions

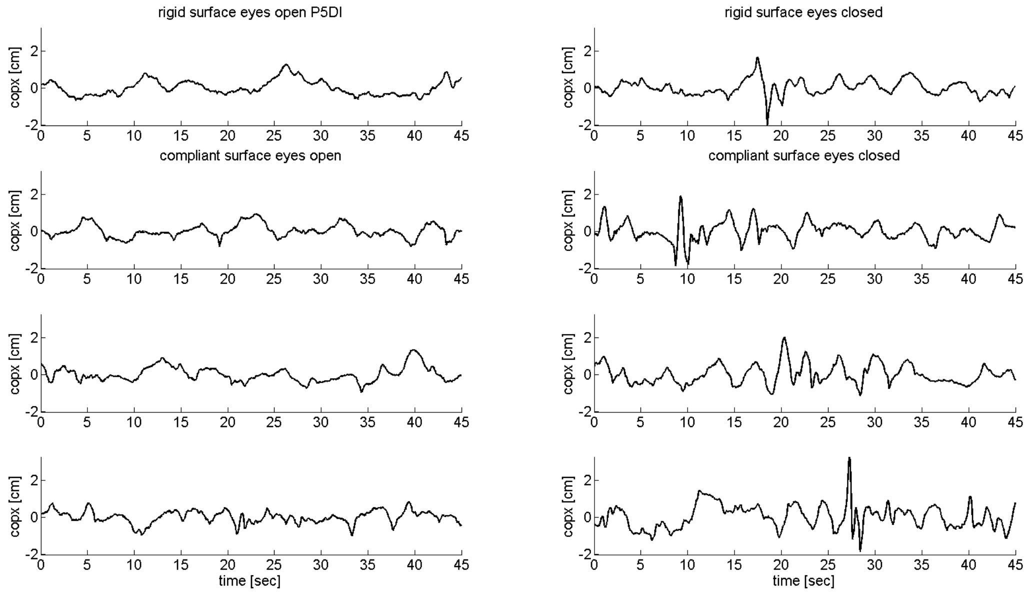

Figure A.12: CoPx Plots of BVL5DI on RS vs. CS and EO vs. EC conditions

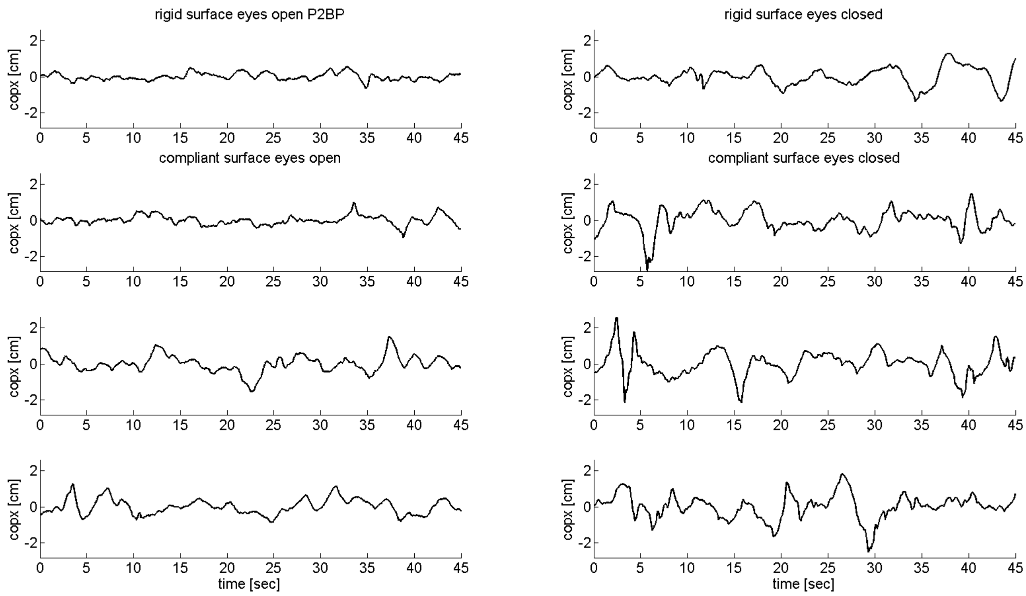

Figure A.13: CoPx Plots of BVL6AM on RS vs. CS and EO vs. EC conditions

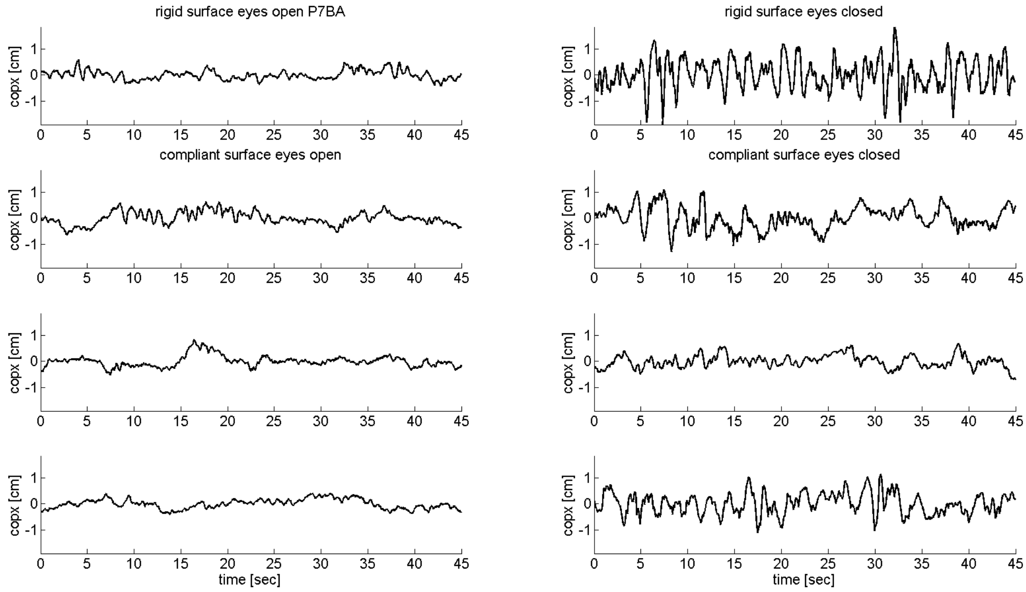

Figure A.14: CoPx Plots of BVL7BA on RS vs. CS and EO vs. EC conditions

APPENDIX B

AUPSD PLOTS OF SUBJECTS

B.1 AuPSD Plots of Healthy Subjects

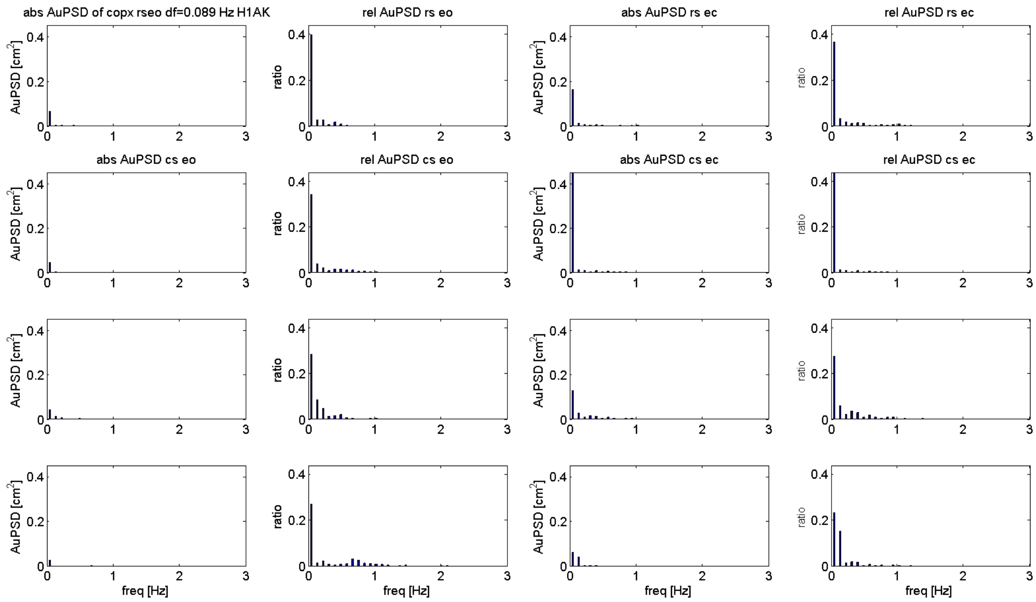

Figure B.1: Absolute and Relative AuPSD Plots of HS1AK on RS vs. CS and EO vs. EC conditions

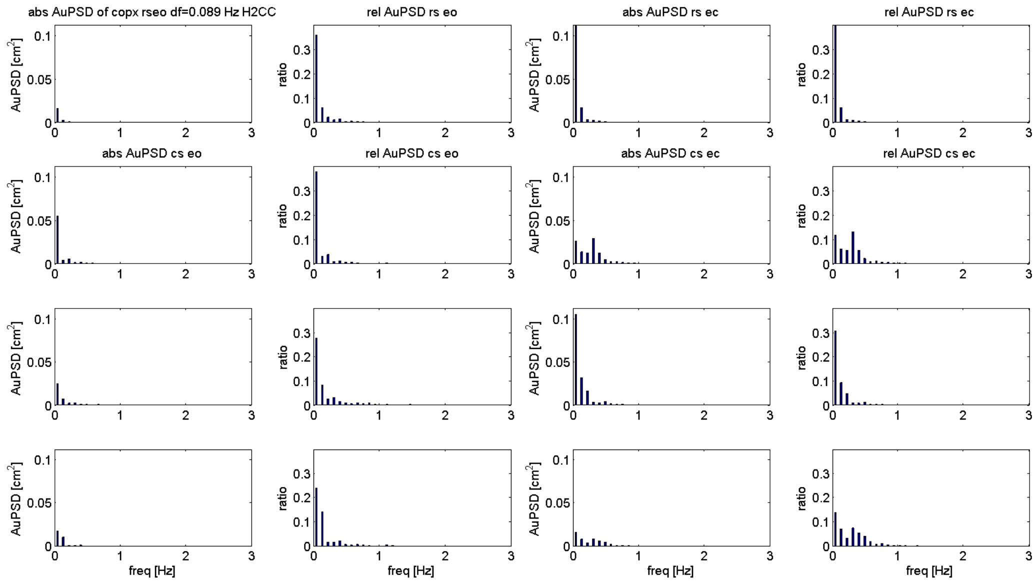

Figure B.2: Absolute and Relative AuPSD Plots of HS2CC on RS vs. CS and EO vs. EC conditions

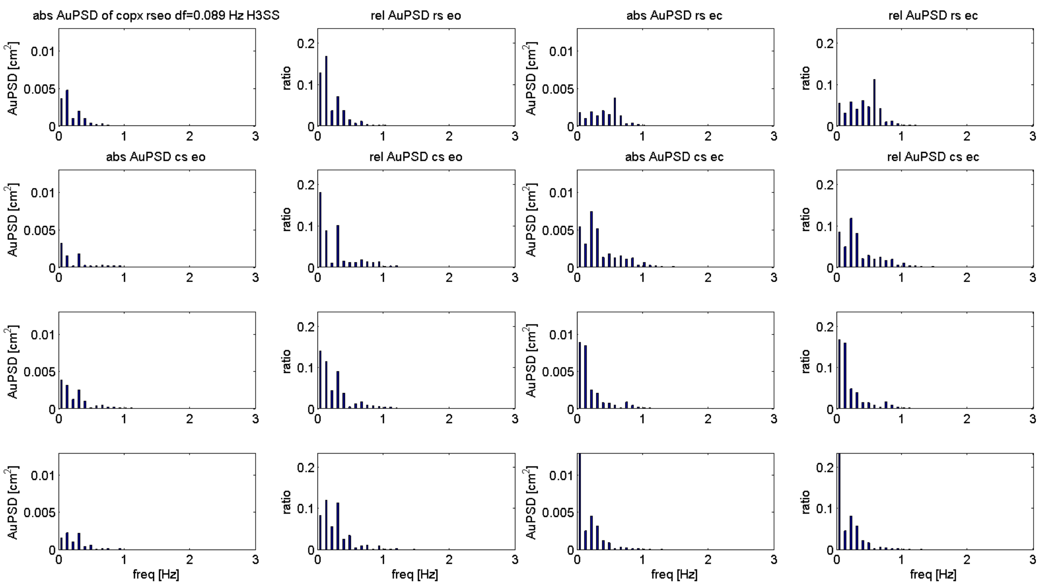

Figure B.3: Absolute and Relative AuPSD Plots of HS3SS on RS vs. CS and EO vs. EC conditions

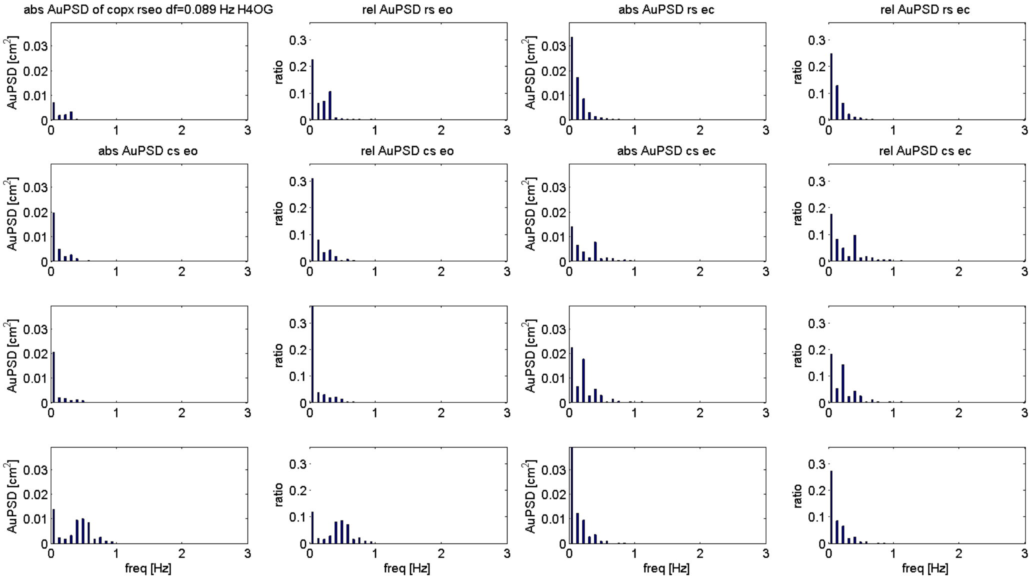

Figure B.4: Absolute and Relative AuPSD Plots of HS4OG on RS vs. CS and EO vs. EC conditions

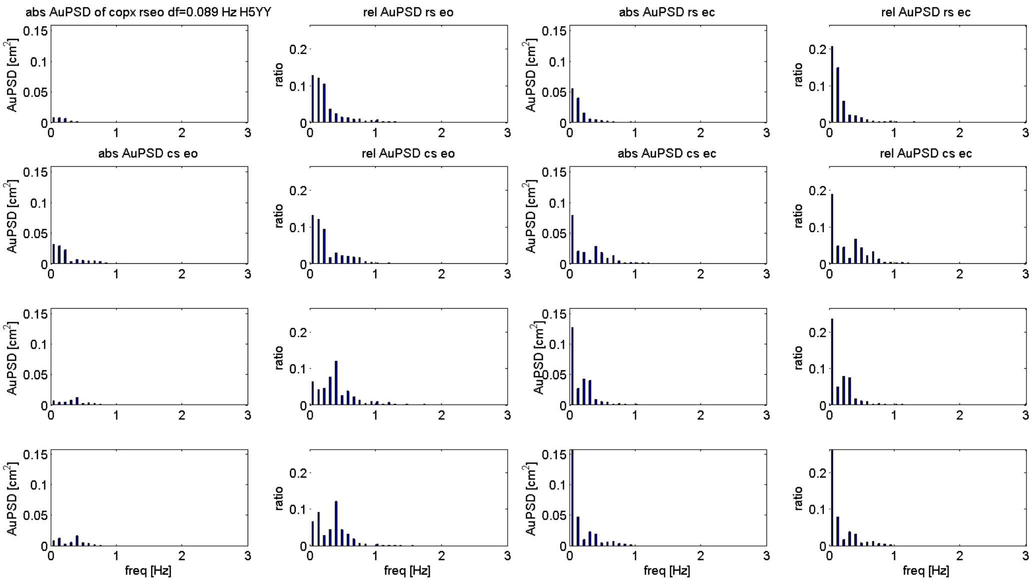

Figure B.5: Absolute and Relative AuPSD Plots of HS5YY on RS vs. CS and EO vs. EC conditions

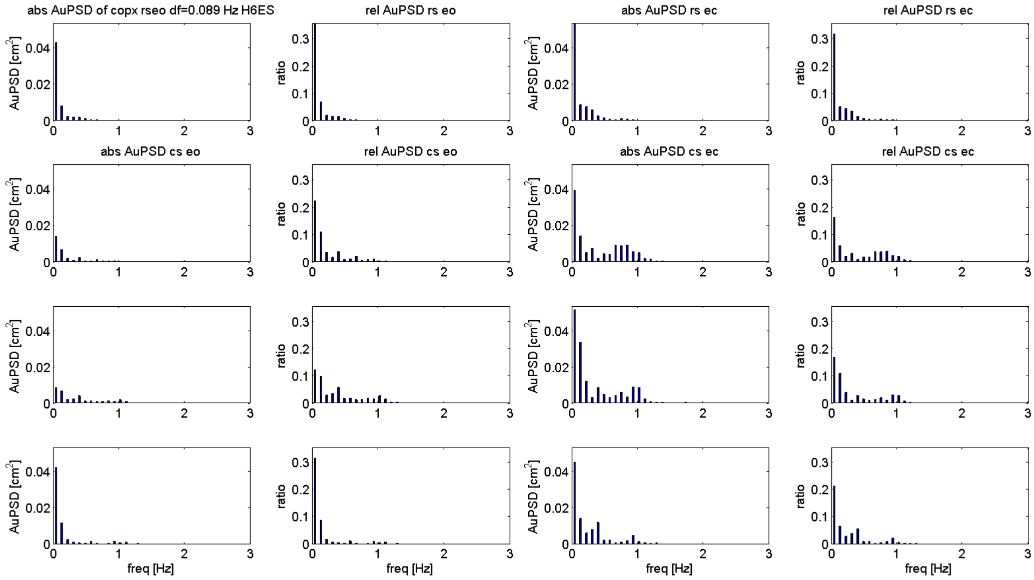

Figure B.6: Absolute and Relative AuPSD Plots of HS6ES on RS vs. CS and EO vs. EC conditions

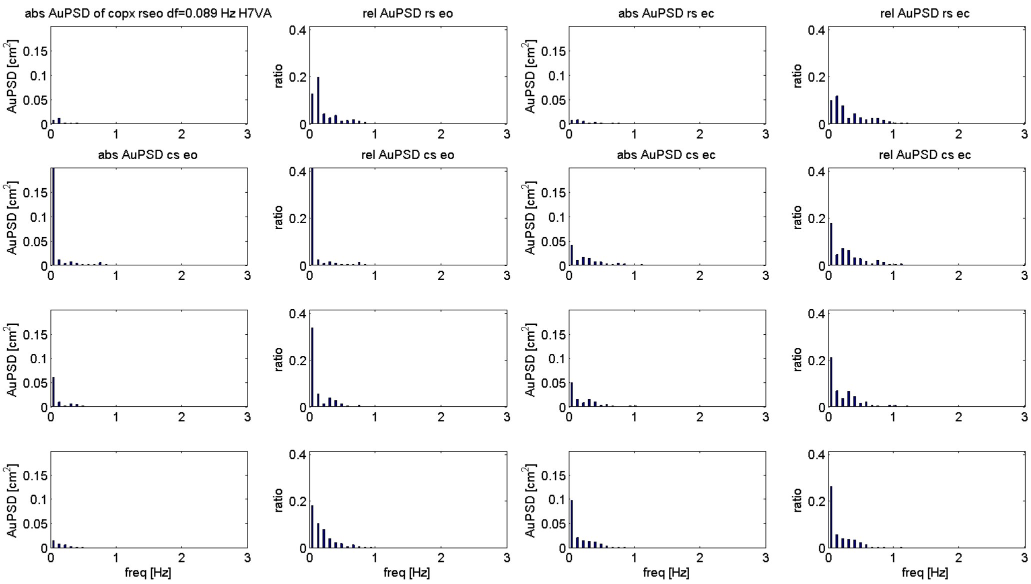

Figure B.7: Absolute and Relative AuPSD Plots of HS7VA on RS vs. CS and EO vs. EC conditions

B.2 AuPSD Plots of BVL Subjects

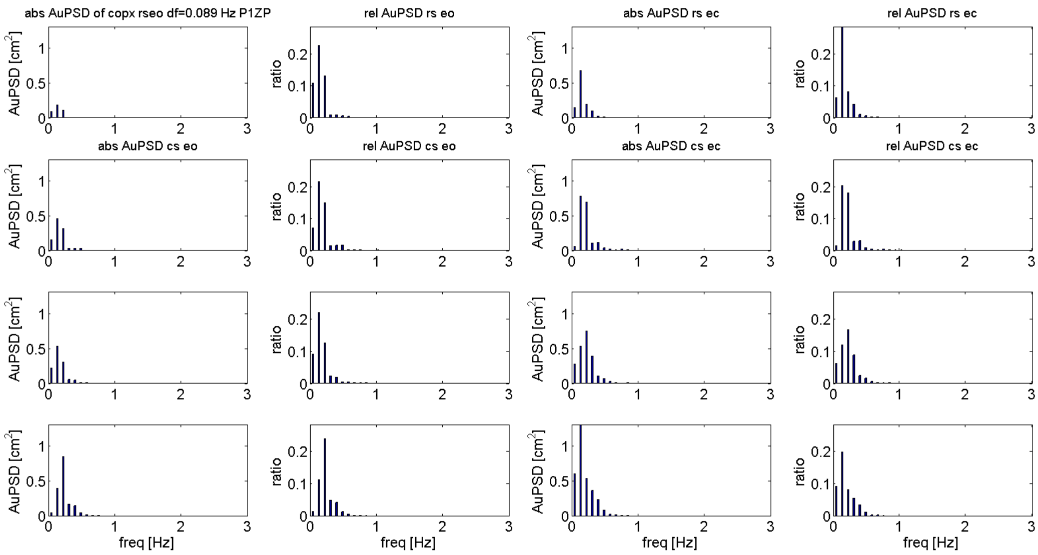

Figure B.8: Absolute and Relative AuPSD Plots of BVL1ZP on RS vs. CS and EO vs. EC conditions

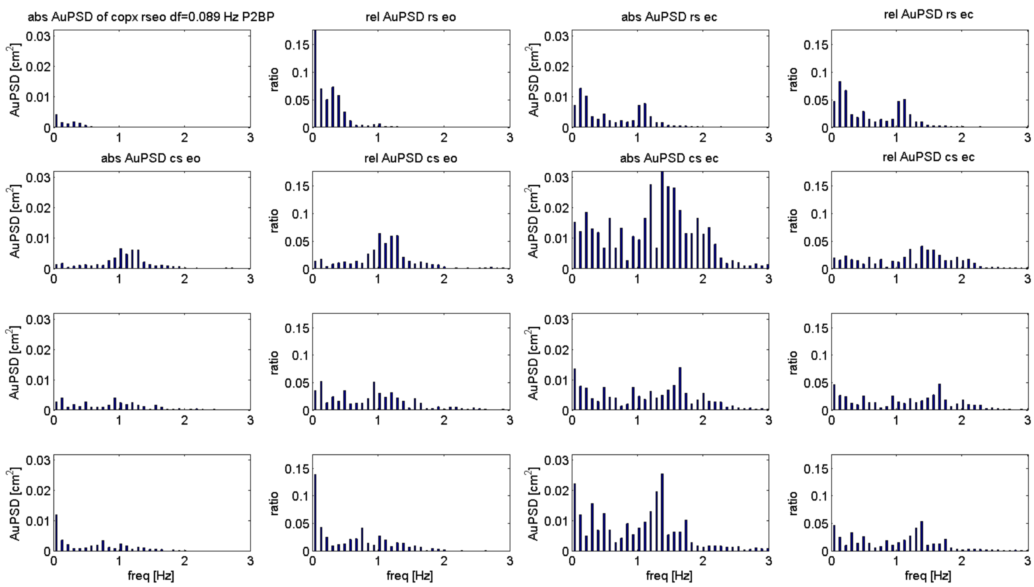

Figure B.9: Absolute and Relative AuPSD Plots of BVL2BP on RS vs. CS and EO vs. EC conditions

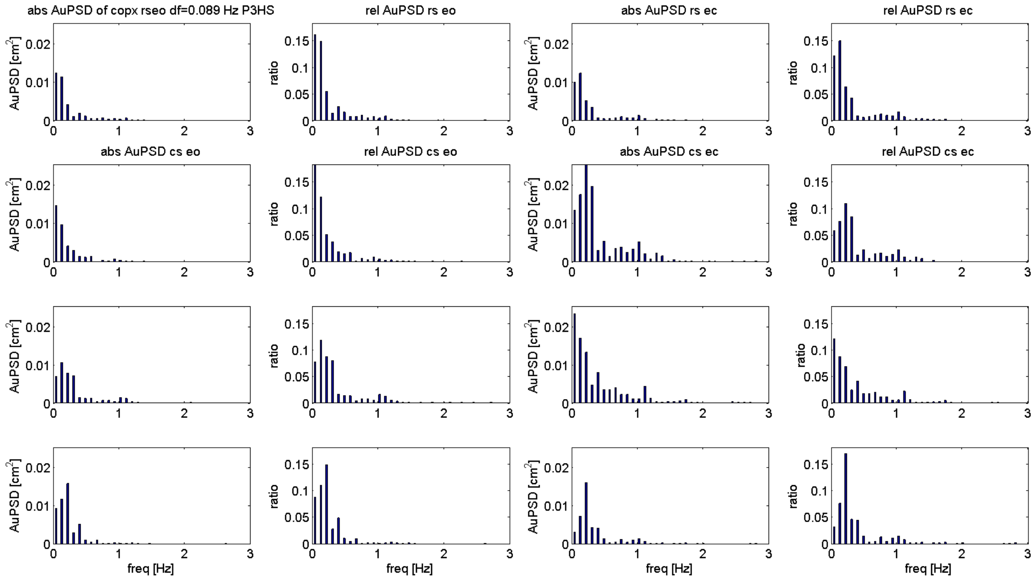

Figure B.10: Absolute and Relative AuPSD Plots of BVL3HS on RS vs. CS and EO vs. EC conditions

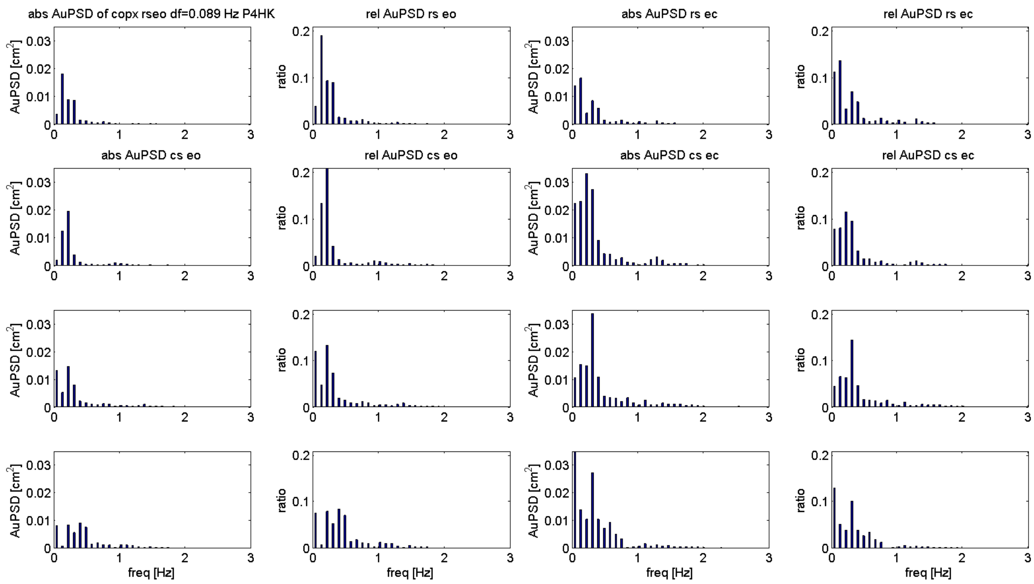

Figure B.11: Absolute and Relative AuPSD Plots of BVL4HK on RS vs. CS and EO vs. EC conditions

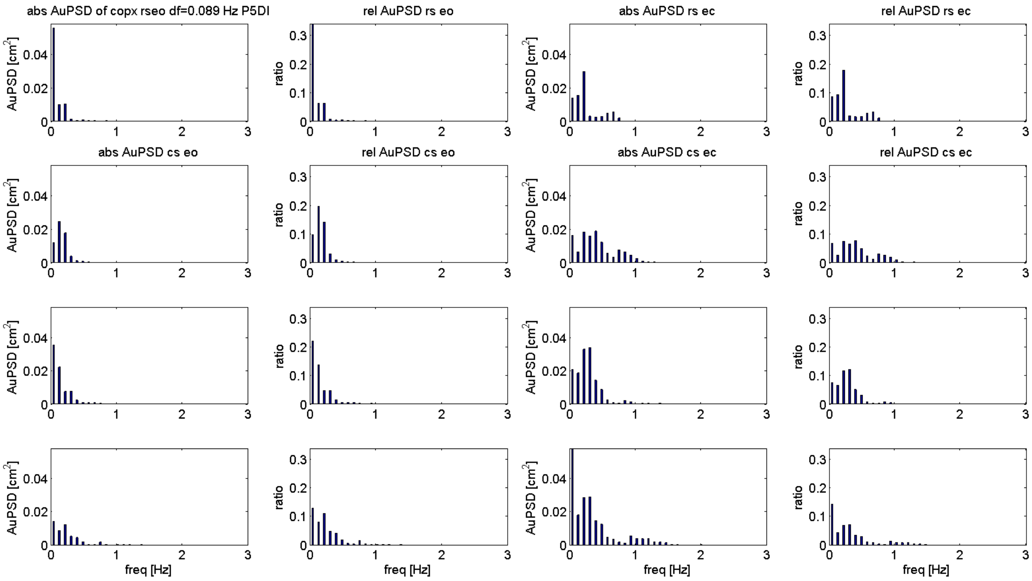

Figure B.12: Absolute and Relative AuPSD Plots of BVL5DI on RS vs. CS and EO vs. EC conditions

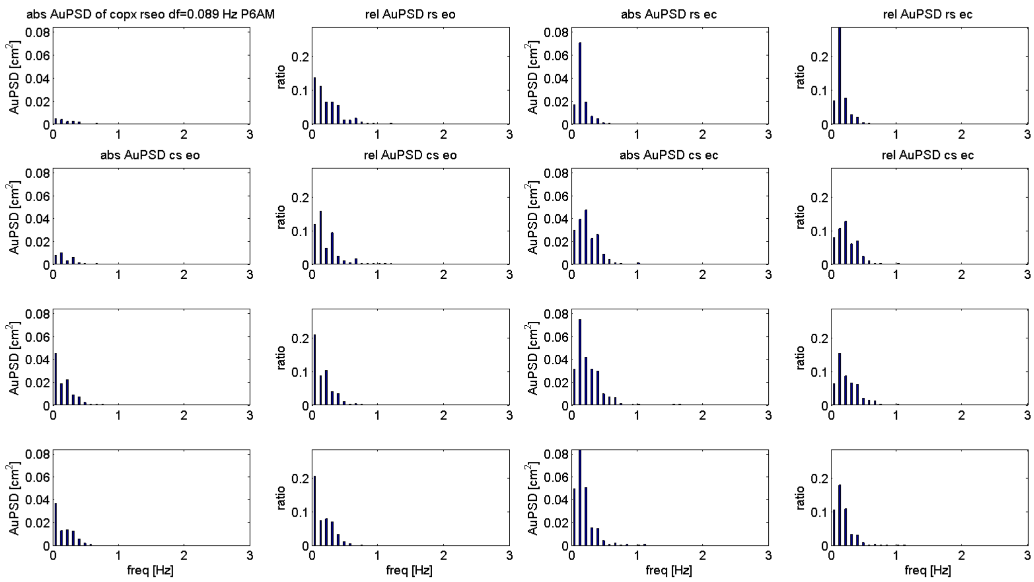

Figure B.13: Absolute and Relative AuPSD Plots of BVL6AM on RS vs. CS and EO vs. EC conditions

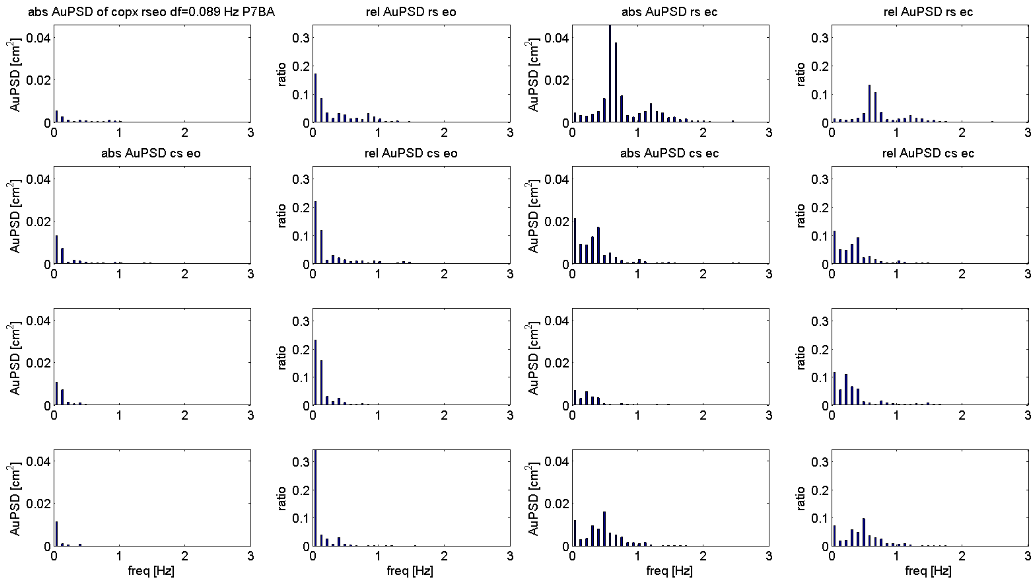

Figure B.14: Absolute and Relative AuPSD Plots of BVL7BA on RS vs. CS and EO vs. EC conditions

APPENDIX C

LIST OF QUESTIONS ASKED TO SUBJECTS BEFORE AND AFTER THE EXPERIMENT

This appendix includes information about the interview parts of the experiments. Subjects were asked some questions to get some basic information like age, weight, length etc. Furthermore, they were also asked more detailed questions. In this appendix, this questions which were asked before and after the experiment were listed.

C.1 Question Asked to Subjects Before the Experiment

- What is your job?
- Do you have any pain or problem?
- Which hand do you prefer to use doing something in general?
- Which foot do you prefer to kick with?
- Is there a sport you regularly do?
- Do you wear glasses?
- Have you had any surgery?
- Do you have a chronic illness?
- Do you feel good?
- Have you had any accidents?
- Are there any medications you use regularly?

If the subject is a patient:

- What are the complaints or problems about your disease?
- What is the diagnosis for your disease?
- How many years have you suffered from this disease?
- Have you ever felt due to your disease in your daily life?

C.2 Question Asked to Subjects After the Experiment

- Do you want to say anything about the tests in general?
- Were tests difficult?
- If you have compared trials in EO and EC condition, in which trials were more difficult? Or, is there any difference between them?
- If you have compared trials in RS and CS condition, in which trials were more difficult? Or, is there any difference between them?
- Have you ever thought that the platform was moving during the trials? If yes, can you describe the movement you felt and say in which trials you felt?
- Have you ever felt a nausea or/and dizziness during the trials?
- Have you ever made any voluntary movements during the trials?
- Were the trials boring?
- Which trial was the most difficult one?
- Did you tired due to trials? If yes, after which trial did you feel tired?
- Is there a question we have forgotten but you want to ask?

APPENDIX D

APPLICATIONS ON FREQD

This appendix part was written for clarifying the function and importance of FREQD metric by some numerical applications. This metric gives us the idea about how a signal is close to a pure sine function that is periodically correlated. If the signal is a perfect sine function, FREQD returns zero. In this part, the change of FREQD value corresponding to the type of component functions of the signal was examined.

Five different signals which was composed of different types and number of functions were generated to compare their FREQD values. First signal is a pure sine function (periodically correlated). However, note that purity of a discrete function depends on its sampling rate due to numerical reasons. Thus, FREQD value was close to zero but not exactly zero for first signal. This function was also used as a base function for following signals. Second function is the sum of three sine functions with unity amplitudes but different frequencies. Since changing the amplitude does not alter the FREQD value, amplitudes of the component functions were taken as unity. Third one is the sum of five sine functions with unity amplitudes but different frequencies (larger the number of the sines, longer is the correlation period of the series). Second and third functions were generated to examine the influence of the number of functions added to signal on FREQD value. The result is that the change of the number of functions which compose the signal is not directly related with the FREQD value. However, adding new function to aggregated signal may change the FREQD value depending on the frequency of new function. The fourth one is the sum of the base function and a white noise signal (uncorrelated with maximum entropy) of same length. White noise was used to understand how an unpredictable function effects the FREQD value. The last one is the sum of the base function and a linear function of same length (correlated at the infinitely long period, -very long term correlation-has a smaller entropy). The explicit functions with corresponding FREQD values and their plots were given in Table D.1 and Figure D.1, respectively.

Table D.1: Matlab Expression and FREQD Values of the Functions

Function No	Matlab Expression of the Functions ("t" was from 1 to 4500)	FREQD
1	sin(4.2*pi*(t/100))	0.0471
2	sin(4.2*pi*(t/100))+sin(0.2*pi*(t/100))+sin(2.1*pi*(t/100))	0.6117
3	sin(4.2*pi*(t/100))+sin(0.2*pi*(t/100))+sin(2.1*pi*(t/100))+sin(1.2*pi*(t/100))+sin(1.8*pi*(t/100))	0.5838
4	sin(4.2*pi*(t/100))+wh_no(t) where wh_no = wgn(4500,1,0)	0.6866
5	0.0012*t+sin(4.2*pi*(t/100))	0.9807

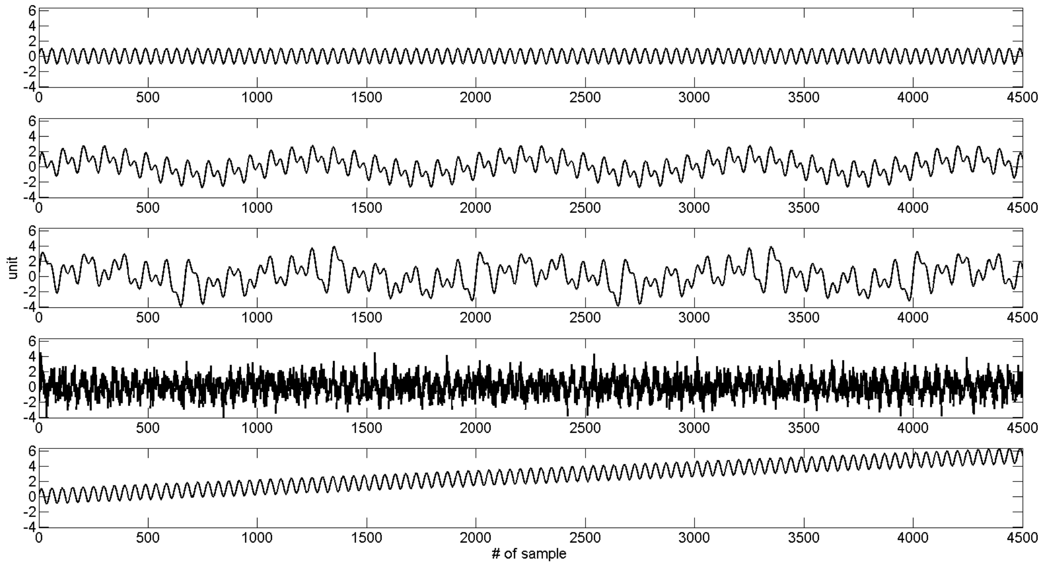

Figure D.1: Plots of five generated signals to examine FREQD metric

The main result is that FREQD is a measure for the periodicity of a function but for the diversity of frequency. Therefore, it may be said that this metric checks the periodic behaviors of the signal within the boundaries of sampling period. Since a high-frequency signal completes more cycles than a low-frequency signal does in a fixed period, its FREQD value is more close to zero. On the other hand, in fourth function white noise affects the regularity of the signal so the FREQD value closes to 1 (higher the irregularity larger the entropy and larger FREQD is). Finally, at last example, base function drifts from its mean due to the linear function (very long-term correlation with a smaller entropy) added. This means that function does not turn back to its initial value. On the contrary, it always move away from there. It is a contradiction for the periodicity of a function so the FREQD value is very close to 1.

We can conclude that FREQD is not sensitive to measure of entropy where we need to check against with an independent metric; i.e., entropy measure or information capacity.