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Recurrence quantification analysis of motor learning and training

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RECURRENCE QUANTIFICATION ANALYSIS OF MOTOR LEARNING AND TRAINING

by

Barry Vuong, B.Eng in Electrical Engineering
Ryerson University, Toronto, ON, 2007

A thesis
presented to Ryerson University
in partial fulfillment of the
requirement for the degree of
Master of Applied Science
in the Program of
Electrical and Computer Engineering.

Toronto, Ontario, Canada, 2009

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Abstract

Recurrence Quantification Analysis of Motor Learning and Training

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Master of Applied Science, Electrical and Computer Engineering

Ryerson University, Toronto, Ontario, Canada, 2009

The goal of this study was to apply recurrence quantification analysis (RQA) to surface electromyographic (sEMG) signals during motor learning and training activities. It has been previously demonstrated that the RQA variable, percentage of determinism (%DET), is related to the synchronization of motor units. It is suggested that %DET will change throughout the motor learning and training process.

As a result, the experiment consisted of two separate parts. The motor learning part required a male subject to train using the Nintendo Wii Fit® software, Wii Fit® balance board and the Nintendo Wii® gaming console. The myoelectric signals were acquired from the peroneus longus (PL) and soleus (S) muscles. During the course of this experiment a soccer simulator and three in-game balance tests were used to evaluate motor learning.

The second part of the experiment consisted of a chronic incomplete spinal cord injured patient from the Toronto Rehabilitation Institute. The subject trained three times a week for fourteen days. Each training session consisted of the subject performing weighted dorsal and plantar flexion.

Both parts of the experiments suggests that there is a decrease in synchronization of motor units after motor learning and training (decrease in %DET). Additionally, the time course of %DET displayed a convergence of levels between the right PL and right S during the virtual environment training. It is concluded that RQA demonstrates the ability to detect motor learning and training. Possible applications for the use of RQA on sEMG signal could be the evaluation of rehabilitation programs. By monitoring the %DET, it may be possible to determine if a particular rehabilitation program is effective for a patient. This could lead to customizable programs, suited for a specific person, in order to increase the rate of recovery.

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List of Abbreviations

%DET	Percentage of Determinism
%REC	Percentage of Recurrence
COP	Centre of Pressure
CNS	Central Nervous System
DM	Distance Matrix
HDS	Hight Density Surface
HSR	High Spatial Resolution
IC	Independent Component
ICA	Independent Component Analysis
JASA	Joint Analysis of EMG Amplitude and Spectrum
MNF	Mean Frequency
MU	Motor Unit
MUAP	Motor Unit Action Potential
MVC	Maximum Voluntary Contraction
PD	Preferred Direction
RMS	Root Mean Square
RP	Recurrence Plot
RPL	Right Peroneus Longus
RQA	Recurrence Quantification Analysis
RS	Right Soleus
SD	Standard Deviation
sEMG	Surface Electromyography
SCI	Spinal Cord Injury
TA	Tibialis Anterior
VE	Virtual Environment

Chapter 1

Introduction

Approximately 700,000 people have strokes each year and stroke is the leading cause of disability in the United States [9]. Often people who have had strokes experience a loss of movement in their limbs or suffer balance impairment. These often require patients to enroll themselves in rehabilitation program to regain partial mobility. With the use of virtual environments (VE) systems, Holden et al. [10] has demonstrated that stroke patients improved after VE training. Similarly, Kizony et al. [11] had attempted to use a VE system for patients with paraplegic spinal cord injury (SCI). The result from this study also showed improvements from the patient after training. There are several other studies which have utilized VE systems to help people who suffer from serious conditions that result in a loss of motor function. As a result, VE systems have started to bridge into the rehabilitation community.

Virtual environments and/or virtual reality systems are often described as immersive, interactive, simulations of environments which are generated by a computer system in real time. Often these generated environments are precisely controlled, accurate, and consistent. In applying these systems to rehabilitation, the term "virtual rehabilitation" was coined in [12]. Application of such systems in rehabilitation demonstrates much promise, but there are some challenges, such as cost and presence of technically trained professionals [13]. As a result, there is a need for low cost VE systems for rehabilitation. Several researchers have purposed that the use of commercially available gaming consoles (Sony Playstation®, Microsoft Xbox®, Nintendo Wii®) may be a feasible substitute for VE-based rehabilitation [12]. More specifically, with the introduction of the Nintendo Wii® system in 2006, there has been an emergence of studies that utilize these gaming consoles [13, 14].

The reason for the Nintendo Wii®'s emergence in the rehabilitation field is its ability to target several key concepts which are relevant to motor learning [13, 14]. These key concepts are repetition, feedback and motivation [15]. It has been established that, practice of movements plays an important role in motor learning. In the case of interacting with VE, the mapping of sensory peripherals to movement occurs during practice [16, 17]. In order to endure long periods of repetitive movement or practice, a subject must be motivated to perform. Since the sole purpose of a gaming console is to provide entertainment, people would be naturally motivated to interact with the VE. Often this motivation is based on achieving a goal which is quantified. In a normal environment (outside of VE), the central nervous system achieves a task by trial and error. This same process occurs during the interaction of VE and a quantified score representing the performance is fed back to the subject. As previously mentioned, this feedback is another key concept which is significant for motor learning and has demonstrated that it helps improve the learning rate of subjects [15].

Concurrent to the key concepts of motor learning mentioned above, there is three stage process, which is interrelated. Halsband et al. [16], has demonstrated that motor learning can be categorized into three stages. The first stage relies heavily on the sensory peripherals and the trial and error process. The next stage consists of the improvement of sensory peripherals and mapping of movements. The final stage often is indicative of reliance of the mapping rather than the sensory peripherals. This often leads to the automation of movement.

Surface electromyography (sEMG) signals play a significant role in rehabilitation [18, 19] or any measurement of muscular activity. The first use of EMG system can be dated back to 1912 by H. Piper, who used a string of galvanometers [2]. By 1929, Adrian and Bronk had developed concentric needle electrodes, which are still prominent in today's studies. In this time period the field of clinical EMG was first established. However, it wasn't until the development of vacuum tube amplifiers, that the field experienced another significant milestone. This resulted in the birth of a quantitative analysis of motor unit action potential (MUAP) and amplitude analysis of EMG. Finally with the introduction of solid state amplifiers and computers, researchers were now able to model and simulate EMG signals. In addition to modeling and simulating EMG signals, researchers were able to apply powerful signal processing tools towards these signals. Such tools can range from decomposition of EMG signals [20, 21] to the use of fractal analysis [22].

Over the course of the development of EMGs, two traditional methods have been demonstrated to be most prominent in the sEMG field. The first traditional analysis is the root-mean-square (RMS) value which depicts the average amplitude of the EMG signal. Although it provides a very useful quantification and has been applied to numerous studies such as fatigue analysis and time response of muscle [23, 24, 25], there are several drawbacks to this method. One specific drawback is its variability, which is associated with the placement of electrodes. This can often be minimized by following guidelines set out by such groups as those within the European Community which sponsored surface EMG for noninvasive assessment of muscle (SENIAM) [26]. Another key drawback in the use of RMS is its limitation to stationary EMG signals. Unfortunately, this parameter can sometimes not be controlled. Finally, the second traditional method of analysis is the calculation of mean frequency (MNF). This analysis has also been described in numerous studies and is subject to the same limitation as mentioned above.

Recently, a nonlinear method known as Recurrence Quantification Analysis (RQA) has been introduced to the biomedical field. This analysis has been utilized in studies involving respiratory rhythms [27], heart beats [28], the neuromuscular system [6, 8, 29, 30, 5, 31], and many more. As suggested by its name, RQA infers a recurrent property in the signal. Biological systems often contain a property of recurrence [2]. In other words, the dynamics of the signal will have hidden repeating patterns. As the signal becomes more complex the recurrent property becomes less probable. The basis behind RQA is the ability to characterize chaos. Chaos theory is popularly referred to as the "Butterfly Effect"; where a butterfly flaps its wings in Australia and creates a tsunami half way around the world. The events from the point at which the butterfly flaps its wings to the creation of the tsunami is considered to be a dynamic system. Dynamic systems can be highly sensitive to the initial condition (the flapping of the butterfly's wings). As the initial condition propagates and grows, this behaviour may appear to be random. This can even occur in situations where the dynamics of the system is defined by the initial condition and contains no random element. When the future dynamics of a system are restricted by an initial condition, it is known as a deterministic system. As a result, RQA has the ability to characterize rhythmic, time varying, complex dynamic and state dependent behaviours [1, 32, 33]. In fact, several researchers have suggested that the motor learning framework is based on concepts and tools from nonlinear dynamical systems [33]. Based on such research, it is postulated that, RQA has the potential to characterize motor learning.

The relationships between RQA and myoelectric signals have been described in several studies [6, 8, 29,

30, 5, 31, 34]. RQA is based on Eckmann et al. [35] recurrent plots (RP): is graphical method to detect repeating patterns. Webber et al. [5] and Nieminen et al. [36] were the first to apply this non-linear analysis to the study of EMG signals. In the proceeding studies, RQA was predominantly used for measuring fatigue. In numerous studies, fatigue has been found to be related to motor unit synchronization. More specifically, as fiber depletes due to fatigue, synchronization occurs to compensate. Referring back to the definition of a deterministic signal, one can suggest that if the initial condition were motor unit synchronization, than RQA would produce a high level of determinism. As a result, several studies have shown that this increase in determinism (Percentage of Determinism) actually occurs when RQA is used to analyse fatigued muscles.

In Gibbs et al. [37] study, the synchronizations of motor units between upper limb and lower limb muscles were compared. It was shown that the lower limb muscles demonstrated a significantly greater probability in synchronization of motor units than the upper limb. This study provided evidence which suggested that lower limb muscles such as the soleus, gastrocnemius, and hamstring are similar with respect to their function compared to upper limbs. As a result, the synchronizations of motor units is dependent on the function of the muscle rather than the anatomical relation to the motor pools.

Unfortunately, there is only a limited amount of studies which involve the relationship between EMG and motor learning. It is the goal of this study to evaluate the effectiveness of RQA on motor learning during VE training on a normal subject. Once general trends are established, the same method will be applied to a patient with incomplete SCI. Based on previous studies, it is proposed that RQA will be able to detect a change during the training.

It is the main focus of this work to determine the following: 1) A change in %DET before and after training, 2) A correlation between traditional analysis and RQA, and 3) the effectiveness of RQA to quantify motor learning.

This Thesis is divided into five chapters: Background, Experimental Set-up, Results, Discussion, and Conclusion. The Background provides a brief introduction to the mathematical concepts behind RQA, motor learning and its use in EMG signals. The results, discussion and conclusion are broken up into two sections. The first section consists of the effectiveness of RQA on motor learning through VE training. The second section consists of the application of RQA on a SCI patient.

Chapter 2

Background

2.1 Recurrence Quantification Analysis

As introduced, Recurrence Quantification Analysis (RQA) is one of the main topics of this work. RQA is an analysis which is based on patterns of recurrence in non-linear dynamic systems. These patterns are visually displayed by a recurrence plot (RP), which was first introduced by Eckmann et al. [35]. There are several parameters that must be taken into account in order to develop a recurrent plot. One example, taken from Webber et al. [1], is shown in Figure 2.1. Figure 2.1A shows the up and down oscillation of sea waves. If one would want to see the recurrent plot when the amplitude of the sea wave is exactly 0.9 ft, then a dot is placed at the point in time where 0.9ft occurs. A recurrence plot can then be developed from this mark Figure (2.1B). As seen in Figure 2.1B, both axes are marked at the 0.9ft amplitude and a dot is placed where the two intersect. This is an over simplified recurrence plot example, and the next example is more practical plot. Building upon the previous example, if the amplitude restriction were to be relaxed to within ± 0.2 ft, then the RP would be Figure 2.2B. Although it is not apparent in Figure 2.2B, there exists a diagonal line across the RP. This diagonal line is more apparent in Figure 2.2A which displays the RP of any amplitude of the exact same height. The significance of the diagonal line is that it is the point where the RP is comparing the signal to itself. In terms of signal processing, this is similar to the the auto-correlation function.

Once again, the examples shown above are simplified. There are several mathematical steps which are necessary before the RP can be derived. The first step is to determine the embedding dimension. The use of

Figure 2.1: Recurrent plot of sea waves [1]

Figure 2.2: Recurrent plot of sea wave with relaxed constraints [1]

mathematical transforms such as, mean, variance, autocorrelation, etc., is considered sufficient represent for a single dimension. However, RQA has the ability to take physiological variables and then map into higher dimensions. Mapping the variables into a higher dimension, D , possibly can yield a richer insight into the system. Typically 10 to 20 is used as the embedded dimension, D , when the source of the signal is from a biological system [1]. The derivation of the recommended biological system is beyond the scope of this paper. It has been suggested by Filligoi et al. [6], that the dimension is directly related to the number of variables interacting with the system of interest. In the case of myoelectric signals, these variables could be the number of motor units, number of muscle fibers for each motor unit, firing frequency, action potential velocity, temperature, etc.

The next step is to time shift the measured signal by λ . λ is a integer time unit and can be estimated by calculating the first zero of the autocorrelation function [30, 5]. Using the estimated λ a matrix G is created

$$G = \begin{bmatrix} x(0) & x(\lambda) & \cdots & x((D-1)\lambda) \\ x(1) & x(\lambda+1) & \cdots & x((D-1)\lambda+1) \\ \vdots & \vdots & \ddots & \vdots \\ x(N-1) & \cdots & \cdots & x(n-1) \end{bmatrix} \quad (2.1)$$

Where $N = n - (D-1)$ and,

$$d(i, j) = |D_i - D_j| \quad (2.2)$$

From the matrix G , the Euclidean distances, $d(i, j)$, between all the possible vector pairs are calculated to form the distance matrix DM :

$$DM = \begin{bmatrix} d(1,1) & d(1,2) & \cdots & d(1,N) \\ d(2,1) & d(2,2) & \cdots & d(2,N) \\ \vdots & \vdots & \ddots & \vdots \\ d(N,1) & d(N,2) & \cdots & d(N,N) \end{bmatrix} \quad (2.3)$$

Finally in order to form the RP, a threshold (RADIUS) is selected. If the $d(i,j) \leq \text{threshold}$, then the pixel at $b(i,j)$ is coloured black. Conversely, if the inequality is false, then the pixel is coloured white. The flowchart of the steps taken is outlined in Figure 2.3. As can be seen, the last step is the quantification of the RP.

Often, a RP contains a convoluted pattern which is difficult to visually analyze. As a result, quantitative descriptors are used to measure them. The two most utilized quantities used in this work are percentage of recurrence structure (%REC) and percentage of determinism (%DET). Visually, %REC is the percentage of black pixels with respect to the total number pixels. Liu et al [8], suggested that %REC is the percentage of the number of recurrent points with respect to the embedded dimension squared. Consequently, %REC is directly related to the selection of the threshold and can reflect the current state of the system [29]. On the other hand, %DET is mathematically indicative of the percentage of points which form a diagonal line structure in the RP [32]. As previously mentioned, the main diagonal line represents the point where the signal is compared to itself, thus, any diagonal line would denote self similar recurrences. The physiological connection of both %REC and %DET will be discussed later in this chapter.

2.2 Muscles & Electromyography (EMG)

Before summarizing past works on RQA with surface EMG (sEMG), a brief overview of muscles and EMG are necessary. Figure 2.4 displays a simplified schematic of the central motor system. As can be seen, the signal pathways are connected from the cortex to the spinal cord and finally to the skeletal muscle.

Figure 2.3: Flow graph of RQA algorithm [2]

At the skeletal muscle level, motor units (MU) play a significant role in motor movements. Motor units consist of alpha motor-neurons within the spinal cord and muscle fiber (Figure 2.4). "The alpha motorneurons are the final point of summation of all the descending and reflex input" [2]. As a result, this motor-neuron determines the firing pattern of the MU. During contraction, it has been demonstrated that MUs are recruited in order of increasing size. This is known as the "size principle" and was first pioneered by Henneman et al. [38]. In the case of muscle fibres, there are two types: Type I and Type II. Type II muscular fibres (sometimes referred to as fast twitch) are used for short bursts of power and speed. Typically, Type II fibres have are large cross sectional areas, have lower volume density of mitochondria and have low resistance to fatigue [39]. It is also interesting to note that weightlifters and sprinters have relatively more Type II fibers in their muscle. Conversely, Type I muscular fibers (referred to as slow twitch) exhibit longer

Figure 2.4: Simplified schematic of the central motor system [2]

endurance than type II fibers. This could be due to the higher volume density of mitochondria and may explain why marathon runners have higher levels of Type I fibers [39]. A comparison of the contractile characteristics of Type I and Type II is shown in Figure ??.

During muscle contraction, the sEMG “sees” a summation of several electrical potential fields from active muscle units. Several studies [2, 40, 22] have suggested that the source of the EMG signal originates from the depolarization zone of the muscle fiber. This depolarization zone is where the potential change occurs in one part of the muscle fibre and is caused by an electric impulse that has propagated along the motor-neuron. As a result, there are two events that influence the recordings of muscle fibre action potential [29]. The first is from the propagation of the electrical impulse (as mentioned above), while the second event is the extinction of the propagation of the impulse. The electrical potential field then travels from the source through biological tissue and then finally gets picked up by the electrodes (Figure 2.5A). Unfortunately this interaction with tissue, as well as the distance between electrodes and muscle fiber causes a spatial low pass filter effect [29, 2, 3]. As can be seen from Figure 2.5C & Figure 2.5D, the different locations of the detection point affect what the sEMG electrode sees.

Farina et al. [29] describe sEMG signals as a global measurement of MU activity, since traditional (bi-polar) EMG systems cannot extract individual MU. These global characteristics (i.e. amplitude, power

spectrum) reflect certain properties of the neuromuscular system [29, 41, 42, 20]. As a direct result of sEMG signals being a global measurement, the recorded signal not only records the target muscle but also the nearby muscle.

Figure 2.5: Biophysical model of the interaction between sEMG electrode and muscle fibers [3]

Often the ability to monitor a motor unit recruitment, decruitment and firing rate with surface EMG electrodes is difficult. Special signal processing techniques known as EMG signal decomposition are required to extract and classify the individual MUAP. This technique may also be applied to invasive needle electrodes. However, due to the invasive nature of needle electrodes, professionally trained staff must be present during the experiment. Additionally the subject may experience discomfort and have an increase risk of infection. Recently, the development of high spatial resolution (HSR) or high density surface (HDS) EMG provides a method that has characteristics which are “the best of both worlds.”

With the use of a HDS-EMG, Nakamura et al. [39] demonstrated that it was possible to decompose MUAP trains using independent component analysis (ICA). ICA is a class of algorithms known as blind

signal separation, which predicts original sources from a set of mutually interfering signals. The assumption is that the mutually interfering signals are linearly mixed with the original sources [43, 44]. What ICA does is it tries to maximize statistical independence of each original source by utilizing a variety of statistical methods. Because ICA is not a crucial part of this study, the theory behind it is left for Appendix Q.

Unfortunately, Drost et al. [45], concluded that, like the needle EMG systems, the use of HSR-EMG to analyze motor unit firing patterns and characteristics is very time consuming and complicated. As a result, there is no systematic process for evaluating the result and thus is not currently suitable for clinical use. However, Drost et al. [45] believes that there is a great potential in HSR-EMG, and it could advance research in such areas as neurophysiology.

2.3 Recurrence Quantification Analysis on surface EMG

Recently, it has been shown that the use of RQA can also reflect properties of the neuromuscular system. RQA is categorized as a non-linear analysis. The advantages of RQA are that the signal is not limited to data size, stationarity, or statistical distribution [30]. As a result it has been suggested by Webber et al. [5] that the advantages of RQA are ideal for use on biological or physiological signals. In most cases the analysis of time or frequency domain often requires the system to be stationary. This requirement is often not true for physiological signals [5]. However, there are some cases where the traditional signal analysis still applies therefore, the use of a combination of linear and non-linear analysis is ideal. Some studies have shown that RQA analysis is more sensitive to the detection of muscle fatigue than traditional spectral analysis [30].

Traditionally, the measurement of muscle fatigue utilizes spectral measurements such as median frequency (MDF) and mean frequency (MNF). It has been suggested that MDF is indicative of the change in conduction velocity of muscle fibers [20]. In other words, the spectral content is hypothesized to provide information regarding the recruitment and/or de-recruitment of motor units [46]. Additionally, the synchronization of motor units during the progression of muscle fatigue is believed to occur. Liu et al. [8] explain that during fatigue the synchronization arises due to the lack of reserved motor units in order to provide for "motor unit rotation." To have the greatest efficiency during loading tasks, motor units alternate in activating muscles. This is known as motor unit rotation. It is believed that synchronization is a substitute for the depleted

motor units. Many studies have shown that there is a decline in MDF during static loading of muscles [5]. Another traditional measurement of muscle fatigue is the root mean square (RMS). RMS has often been considered as a relationship between contractile force and EMG amplitude. Depending on the particular muscle, Lawrence et al. [47] have demonstrated that there is either a linear or a curvilinear relationship.

In most of the literature with respect to sEMG data, RQA has only been employed to measure muscle fatigue. In these studies, the experiment involved either a loading test or dynamic exercises. As previously mentioned, the two most frequent parameters in RQA which have been exploited are percentage recurrence (%REC) and percentage determinism (%DET). It has been speculated by Webber et al. [5], that %REC is related to isometric lengths of muscle; however there has been no experimental validation. Conversely, %DET has been a well studied measurement found in heart rate variability, breathing patterns, electroencephalograms, etc. The motivation behind the use of %DET is the fact that it has the ability to detect hidden patterns in complex nonlinear signals. It has been suggested in several papers [6, 8, 30, 5, 31] that %DET is related to the synchronization of motor units in muscle. This synchronization model of the muscle to sEMG environment was proposed by Farina et al. [3]. The result from the aforementioned literature show that %REC remains constant throughout the fatigue tests. On the other hand, it was shown that %DET had increased during the course of the experiment. Webber et al. [30] compared both the linear and non linear measures and found that %DET was able to estimate the initial start of muscle fatigue earlier than the spectral analysis. Similar results have been reported in other fatigue related experiments [6, 8, 30, 5].

Another experiment which consisted of sEMG and RQA, was performed by Filligoi et al. [6]. However, the objective of this study was focused not on fatigue, but rather on hidden patterns during isometric contractions. There were two types of contraction involved in this experiment; constant and non constant force. The non constant force required the subject to contract so that the amplitude of the EMG signal resembled a trapezoid. The results of this experiment demonstrated that during contraction at a constant force, %DET continuously increase throughout the contraction. Although this trend also occurs during fatigue, Filligoi et al. [6] that "... %DET initial values are always insensitive to the force level [and] may be interpreted as an expression of the relative independence of neuromuscular system organization from the requested muscle output." Unfortunately during the non-constant force, Filligoi et al. [6] experienced unexpected results and did not draw any conclusion. However, it was shown that during the ramping phase of the non-constant force, MDF appeared to fail to quantify the signal, whereas %DET could still quantify

the signal.

In the Felici et al. [31] experiment, the subjects consisted of weightlifting athletes and control groups. The most significant results from this experiment were from the weightlifting athletes whose sEMG traces displayed burst-like waveforms during the start of the contraction. It was suggested by Felici et al. [31] that these bursts were associated with manifestation of some groupings of motor unit activity. As a result of this burst-like pattern, it was shown that %DET increased.

Until this point all of the previous studies which have been presented (with the exception of Liu et al. [8] required one-day training sessions. The experiment by Liu et al. [8] is the only study that involved multi-day trials with the utilization of RQA on muscles. The experiment evaluated RQA on subjects who exhibited lower back pain. %DET was assessed before and after 12 weeks of active exercise therapy. It was previously demonstrated that after active exercise therapy, the patients' lower back pain subsided [18]. The results of Liu et al. [8] revealed a decrease in %DET in patients after therapy and suggested that it could be possible to assess therapy programs using RQA.

2.4 Relationship between %DET and muscle contraction

In Del Santo et al. [4], L-acetylcarnitine (L-Ac) was injected into the extensor carpi radialis. If an initial injection of saline were to occur before the L-Ac, recurrent inhibition would occur. Recurrent inhibition is defined as an excitement of a population of neurons from a second population of neurons. This in turn excites the original population of neurons. As a result, this causes a pharmacological induced synchronization of motor units. It has been shown that there is a high correlation between the %DET and motor unit pairs. Additionally, there was a substantial increase in %DET during L-Ac injections relative to the control saline injections Figure (2.6).

This increase in %DET was also exhibited in the sustained contraction data from Webber et al. [5]. In Figure 2.7, it can be seen that % DET increases as time progresses. This figure depicts one of the subjects during heavy loading at time 0.

Figure 2.6: In Del Santo et al. [4] A) injection of L-Ac experiment B) injection of saline (control) experiment.

Figure 2.7: The time course graph %DET of heavy loading on biceps from Webber et al. [5] experiment.

This same increase was also demonstrated by Filligoi et al.[6]. In their work, the first and last seconds of a sustained (isometric) contractions were analyzed using both linear and nonlinear analysis. It can be seen from Figure 2.8 that there is a decrease in the MNF and an increase in %DET between the initial and last seconds. As previously stated, several studies have suggested that this increase maybe due to fatigue.

On the other end of the spectrum, there have been some studies on sEMG signals from dynamic contractions. One important factor in the study of dynamic contraction, which has created difficulties, is the effect of changes in muscle length, force [48], and tissue thickness [49], with respect to sEMG signals. It was shown by Bonatio et al. [7] that this factor contributed to a frequency modulation of the sEMG signal within

Figure 2.8: Filligoi et al. [6] comparison of first (left) and last (right) second of sustained contraction. *Top* time domain of EMG signal, *Middle* Recurrence Plot, *Bottom* Power Spectra.

each burst cycle. Christensen et al. [48] attempted to use classical spectral analysis to characterize both dynamic and static contractions. Unfortunately, both MNF and MDF were the same for their corresponding exercises. It is believed that, due to the above factors, the experimental paradigm can no longer be assumed to be a wide-sense stationary signal. As a result, classical spectral tools are considered to be invalid and non-stationary analysis must be employed.

If one were to take this shift to lower frequencies from Bonato et al. [7] and the theory which has been presented, one might suggest that fatigue would be a major factor. Attempting to relate this to RQA analysis, it would be predicted that %DET would increase over the time course of dynamic contraction. In fact, Liu et al. [8] demonstrated that this did indeed occur. Figure 2.10 displays the %DET during the first 10s and the last 10s of the dynamic exercise.

Bonato et al. [7], has shown that a time-frequency analysis could be used to assess dynamic contractions. After validation from simulated sEMG data, it was found that the Choi-Williams transform provided the most optimal result. Consequently, the Choi-Williams transform was employed on sEMG data of knee flexion-extension cycles and the results are shown in Figure 2.9. This figure displays four consecutive bursts

of sEMG signal and it can be seen that there is a pronounced power spectral density near the lower frequency spectrum. Similar results were demonstrated using a wavelet transform [48].

Figure 2.9: Bonato et al. [7] time course of dynamic contraction using Choi-Williams transform.

2.5 Motor Learning through sEMGs

Before presenting previous studies on motor learning through sEMG signals there are several concepts regarding motor learning which must be introduced. There have been a number of studies which have focused on the time course of motor learning [50, 16, 51, 52] and several more studies which focused on the internal modeling of motor learning [50, 16, 53, 54]. One specific study, which was produced by Halsband et al.[16], suggested that motor learning is broken down into three stages.

The initial stage is highly reliant on sensory feedback and often leads to a slower performance. This is mainly due to a trial and error process in which a "... novel establishment of perceived sensory cues with

Figure 2.10: Liu et al. [8] %DET of the first 10s (black bars) and last 10s (gray bars) in a dynamic exercise.

the correct motor commands" [16] takes place. The result is often irregular movements and variable time performance.

The trial and error process is "closely related to attention, decision and selection of movement, sensory feedback processing and working memory" [16]. This gradual learning of sensory mapping to correct movement is known as the intermediate stage. However, the performance is still unskilled, slow, and heavily reliant on sensory feedback. Mussa-Ivaldi [55] suggested that trial and error experiments could be used to update the parameters of an arbitrary initial model. This updating occurs until an optimal or satisfactory performance is attained.

Finally the last or advanced stage of motor learning consists, of sensorimotor maps becoming stronger and stored in long-term memory, as the subject practices. This process often leads to rapid, automated and skillful performance. As a result, sensory feedback is less involved. Mochizuki et al. [56] hypothesized that there is an increase in motor unit synchronization during postural sway when the eyes are closed. This was based on the relationship of postural sway and contracting forces in the anterior/posterior and medial/lateral direction [57].

These three stages are a part of two forms of motor learning; explicit and implicit learning. "Explicit learning involves conscious recollection of previous experiences" [16]. While, "implicit learning is defined as an unintentional, non-conscious form of learning ..." [16].

If the subject were to practise extensively (days and/or weeks), motor learning patterns would demonstrate that there is a rapid improvement in short-term learning and a slow improvement as learning progresses (long term). It is interesting to note that a similar pattern was seen in the visual learning process [58]. These stages of motor learning seem to exist regardless of age.

Another experiment consisting of motor learning through the utilization of sEMG was demonstrated by Throughman et al. [59] and Betker et al. [60]. Both experiments consisted of subjects hitting targets in a virtual environment while measurements of several sEMG signals from different muscles were taken. A tuning function was calculated by taking the average activity (RMS) of a muscle during initial movement as a function of direction. This vectorization is then summed and the resultant vector is denoted as the preferred direction (PD). Several studies have found that during non-perturb movements, the PD remained constant during the training [59, 60]. Conversely, the PD displayed a clockwise rotation between the initial perturb training and the later stages of perturb training. Upon closer inspection Throughman et al. [59] noted that after perturb training the sEMG activity occurred later in time with respect to the initial perturb training. In Betker et al. [60], the PD rotated either clockwise or counter clockwise. This may be due to the fact that Betker et al. [60] were measuring muscles located in the lower half of the body compared to Throughman et al. [59] who were measuring the upper half of the body.

After a review of several previous works on RQA [6, 8, 29, 30, 5, 31], the only quantification variable which appears to be useful was the %DET. This is mainly due to the fact that %DET demonstrates a change during the course of strength training. This was not the case for the percentage of recurrence variable, as it displayed insufficient change during the course of training. Additionally, an increase in %DET has shown to be correlated with motor unit synchronization. It was hypothesized that RQA would be an effective tool in measuring the change motor learning through virtual environments. It is believed that as training progressed the %DET would increase. As previously mentioned, several studies have concluded that one of the relationships between %DET and physiological phenomenon was motor unit synchronization. Consequently, one possible outcome could be an increase in synchronization during training in order to improve efficiency.

Chapter 3

Experimental Set Up

In this study, there were two experiments which were conducted to evaluate the effectiveness of RQA on motor learning and muscular training. The objective of the first experiment was to evaluate RQA in a virtual environment (VE) and is outlined in section 3.1. The second experiment was the application of RQA on a SCI patient undergoing strength training exercises and is outlined in section 3.2.

3.1 Virtual environment training

3.1.1 Subjects

The single case study consisted of a right handed male in his early twenties who has no history of postural or neuromuscular problems. The subject had very limited exposure to the virtual environment before the experiment and there was a six-month gap between the last exposure and the start of the experiment.

3.1.2 Experimental Protocol

The training schedule consisted of the subject undergoing three weeks of training in the virtual environment. It has been shown by Reilly et al. [61] that a non-professional soccer player's performance varies during different times of the day. As a result, the training in this experiment was scheduled at the same time each day in order to maintain a consistent performance by the subject.

It was previously mentioned that motor learning often requires repetition in order to promote motor

learning. As a result, the VE training was performed for 18 consecutive days. During a single day session, the participant was subjected to a soccer training trials and two balance tests. For each session, two balance tests would be chosen, at random, by the software. There were a total of five possible balance tests that the participant could have performed (the details of each test will be presented in the next section). During the last day of the experiment a second set of balance tests were performed after the soccer training game. At the start of the experiment, the subject was required to perform the two balance tests. After the completion of the balance tests, there was a two minute break before the commencement of the soccer training. The soccer training consisted of two difficulty levels: beginner and advance. The beginner difficulty level was utilized during the first five days of the experiment. At this difficulty setting, 14 soccer sessions were performed by the subject each day.

On the other hand, the advanced difficulty setting was used in the remaining portion of the experiment (13 days). The soccer training sessions at this difficulty setting had consisted of 10 games. At the mid point of the soccer training session (game 7 for beginner and game 5 for advanced), a five minute rest period was given in order to avoid fatigue in the muscles. Finally, the transition from beginner to advanced difficulty occurred when the performance of the subject were near the upper score limit (which was noticed on the 5th day of training). Throughout the whole experiment a video recording of the VE was facilitated using a built-in iSight webcam on an Apple Macbook laptop.

Figure 3.1: Graphical representation of the experimental setup for the virtual environment experiment

3.1.3 Virtual Environment

In this study, the Nintendo Wii Fit® software along with the balance board and Nintendo Wii® system were employed to generate the Virtual Environment. The Nintendo Wii® balance board is composed of four strain gauges located at each corner of the base. These strain gauges have a sensitivity of 500g and a sampling rate of 100Hz [62]. The centre of pressure (COP) was calculated and mapped to a virtual sprite or avatar in the VE. The VE is then displayed on a LCD TV (Figure 3.6). Before the initiation of the balance tests and soccer training, the balance board had to be calibrated. This calibration was necessary in order to scale the subject's physical COP movement range to the boundaries of the VE. The subject was also instructed to keep both feet on the balance board during the course of the experiment.

Test A: Basic Balance Test

Figure 3.2: The basic balance test environment

As was previously mentioned, the balance test contains five different tests which the software chooses. The first test was denoted as Test A in this experiment, but referred to (in the Wii Fit® software) as the basic balance test. The VE in this test displays a left vertical bar and a right vertical bar which denote the weight between the left leg and right leg. When the subject shifts his/her weight more to the right, the right vertical bar rises. The opposite occurred when the weight was shifted to the left. As part of this test the subject has to shift their balance until the vertical bars hit a certain range (horizontal bars). When the vertical bars are within the horizontal bar range, the subject must hold this position for three seconds (3.2). As the subject progresses through each target the difficulty increases by decreasing the surface area of the target and having the subject keep an equal weight on both legs. There were a total of five targets which the subject was instructed to hit within 30 seconds to complete the entire task. At each target, the response

time for a successful completion of the task was recorded by the software. These response times may provide evidence of motor learning [63]. Additionally, while the subject attempts to complete a target, two types of contractions would exhibit; dynamic and sustained. It would be interesting to observe the differences in the two types of contractions with respect to motor learning.

Test B: Agility Test

Figure 3.3: The agility test environment

This next training session had similar qualities to the VE reported in Betker et al. [60]. In this test there is a box centered on the screen and is broken into four quadrants. The subject's COP was linearly mapped to a circular sprite. As part of this test, the subject is instructed to intersect the sprite with the virtual targets which appear on the screen. The difference between the experiment of Betker et al. [60] and Test B is that Test B contains more targets on the screen at one point in time. Similar to Test A, as the subject progresses through each stage the difficulty also increases and there is a 30 second time limit (defined by the VE). The highest stage that the subject is able to reach is recorded. This is considered as a measure of the subject's performance.

Unlike Test A, this test required the subject to control both his lateral and anterior/posterior COP. This may result in a different sEMG activity compared to Test A.

Figure 3.4: The single leg balance test environment

Test D: Single Leg-Balance Test

In this test, the subject is required to stand on a single leg for 30 seconds. This 30 seconds was restricted by the VE and could not be changed. The screen displays a vertical box with a line through the centre. Accompanying this is a circular sprite which represents the lateral movement of the subject's center of pressure. As time progresses, a line traces the deviation of the subject's lateral movement. At the end of the test a game score measurement is displayed. It is assumed that this measurement is based on the subject's standard deviation from the midline and is considered as a measure of performance. The significance of this test is its ability to be performed outside the VE construct. Additionally, previous studies have shown that the soleus is one of the predominate muscles for postural tasks and has demonstrated motor unit synchronization during postural tasks [56].

Soccer Training

The soccer training used in this experiment is a simplified simulation of a soccer goaltender stopping soccer balls. In the VE there is an avatar which represents the COP of the subject. During the course of the training, there are three possible locations where the balls "fly" at the avatar; extreme left, center or extreme right. The subject is instructed to shift his/her balance, in order to intersect the virtual soccer ball with the avatar. At random times throughout the training, obstacles such as a soccer cleat "fly" towards the subject's avatar. If the subject hit these objects, points are deducted from the total score. At the end of each soccer session, the total score is recorded.

Figure 3.5: The soccer training environment

The length of time in a single soccer training session varies depending on the initial difficulty setting. In the case of the beginner setting, the session lasts approximately one and a half minutes. On the other hand, the advanced setting lasts approximately two minutes. Another difference between the difficulty settings are the number of soccer balls and the rate at which these balls fly at the avatar. For the beginner setting, there is a total of 79 soccer balls to hit, which results in a maximum score of 555 points. These soccer balls fly at a lower rate with respect to the advance difficulty. Conversely, for the advance setting the total number of soccer balls were 118 and the maximum possible score is 655.

On a single day the subject endured 20 minutes of soccer training. This consisted of approximately 14 soccer trials on the beginner setting and 10 trials on the advance setting. In other words, the soccer training game was repeated several times. Each time the subject perform a single soccer training game, it would be considered as one trial.

3.1.4 Surface EMG Measurements

The inter-electrode distance was approximately 2 cm and a permanent marker was used to mark the location of the electrode to ensure continuity of placement throughout the experiment. There were two sets of Ag/AgCl electrodes used in this experiment (See Chapter 4.1.7). The first set electrodes (MVAP-II, MVAP Medical Supplies) were employed during the first 12 days of the experiment. For the remaining 6 days a second set electrodes (Red Dot™, 3M™) were used.

The EMG acquisition system (CleveMed BioCapture®) was a wireless module which was clipped on the subject's pocket during the course of the experiment. The EMG signal was sampled at 769 Hz or 800 Hz at 12 bits (More details regarding this change is seen in section 4.1.7) with a voltage range of ± 3 mV. The receiver module was connected to a PC desktop via USB. A proprietary BioCapture® software was then utilized to interface the wireless device and acquire the signal onto the computer. Finally, these signals were exported and used for further analysis. Unlike most EMG acquisition system the BioCapture® system did not contain a bandpass filtering stage. This may be due to the fact that this system is a multi-purpose device which can be used for collecting other biological signals (EEG, ECG, etc.). As a result, a 6th order Butterworth bandpass filter with a range of 10 Hz to half the sampling frequency was implemented in MATLAB® and employed on each EMG segmentation.

Before the placement of the sEMG electrode, the site of interest was cleansed with an abrasive gel and wiped off with a 70% isopropyl alcohol pad. This reduced the impedance of the skin and improved the signal-to-noise ratio. According to Farina et al. [40], the electrode location plays a critical role in attempting to capture EMG signals during dynamic tasks. From simulations, Farina et al. [40] were able to determine that a 15 mm shift in the muscle under the electrodes could vary the resultant EMG signal. As a result, disposable Ag/AgCl sEMG electrodes were placed on anatomical landmarks [26] for the right and left peroneus longus (PL), and soleus (S). The reference electrode was placed on the ankle bone near the Achilles tendon. The placement of the electrode followed the electrode placement standard defined by SENIAM [26]. It has been suggested that the soleus muscle assist in flexing the ankle joint (plantarflexors). However, the peroneus longus is responsible for the movement of the sole of the foot away from the median plane [64]. As a result, these two muscles are be candidates for measuring the change in myoelectric activity with respect to motor learning.

3.1.5 Data Analysis

All RQA analysis of sEMG signals were analyzed by a C++ program [65] which had been used in several past studies [6, 8, 31]. In order to achieve optimal results from RQA, seven parameters were selected carefully. For more detailed descriptions of these parameters, refer to software documentation [65].

During the course of the experiment there were five parameters which were kept consistent. The first parameter was the embedding dimension which was set to 10. As can be seen, this value falls within the

range that Webber et al. [1] suggested for biological systems. The second parameter was the norm and this was set to Euclidean norm. In other words, the Euclidean distance between the two vectors was used to calculate the distance matrix. Third, the rescaling parameter was set to the maximum distance. This enabled each element in the distance matrix to be divided by the maximum distance in the distance matrix. The fourth was the line parameter, which was set to 2. This meant that two points that were diagonal to each other were considered to be deterministic. Finally, the last consistent parameter was the radius, which was set to 10% of the maximum distance in the recurrence plot. It is worth noting that these parameters were also used to Lu et al. [8].

The first of the two parameters which varied during each EMG analysis was the window length. Depending on the type of test or if it was the soccer training, different segmentation lengths of the EMG were employed. In the case of Test A, there were three different segmentations. The first segmentation was the entire length of time it took the subject to hit each target. This was based on the response time recorded by the game. The next two segmentations were categorized as either dynamic or sustained contractions. Since it was known that the subject would have held their balance (within the target range for three seconds,) it was assumed that the three second window was composed of sustained contractions. Any time period before the three seconds was segmented and assumed to be dynamic activity.

The analysis for Test B consisted of visually determining the initial burst EMG activity from the signal. A segmentation window of the first 2 seconds (either 1538 points or 1601 points) of the activity was then applied and processed using the RQA software. The final burst of EMG activity was visually determined and the first two seconds of that signal was also segmented and analyzed. The same segmentation procedure was applied to the soccer training.

The Test D analysis was very similar to that of Test B. Both of these analyses consisted of segmenting the initial two seconds of EMG activity. However, an additional segmentation was applied to the mid-point of the data and the final two seconds of the EMG signals.

All segmentations were done in MATLAB® and exported into a data-file where the RQA software analyzed the segmented EMG data. The last parameter was the delay (λ). As previously stated, this parameter can be estimated by finding the first zero crossing of the autocorrelation function. The significance

of choosing the first zero crossing of the autocorrelation is it uncorrelates the elements each row of the G matrix. This analysis was also done concurrently with the segmentation processing in MATLAB®.

Finally, two traditional EMG analyses were employed on the data in order to compare the results from RQA. The first traditional analysis was the root mean squared (RMS) value and was calculated using the following equation [66]

$$RMS = \left[\frac{1}{N} \sum_{i=0}^{N-1} x^2(n) \right]^{\frac{1}{2}} \quad (3.1)$$

Where, the EMG signal is $x(n)$ and the window length is N samples. The RMS has been described to represent the average amplitude of the EMG signal [66]. This value can be related to power, but may not be valid for non-stationary signals [66].

The second method was the mean frequency (MNF) of the EMG signal. It has been well established that there exists a relationship between MNF and conduction velocity of the muscle fibers [67, 21]. Additionally, studies show that the MNF is a more reliable measure than median frequency [34, 68]. The evaluation of the MNF was calculated using the following equation [8]

$$MNF = \frac{\sum A_i f_i}{\sum A_i} \quad (3.2)$$

Where, A_i was the spectral amplitude and f_i was the frequency value.

3.2 Spinal Cord Injury Patient

The second case study involved a chronic incomplete spinal cord injury (SCI) patient from Toronto Rehabilitation Institution. He had mobility in his limb and could perform daily physical activity such as walking.

All training with respect to the patient was performed at the rehabilitation institute and was approved by the Toronto Rehabilitation Institution ethics committee.

3.2.1 Experimental Protocol

Figure 3.6: Graphical representation of the experimental setup for the spinal cord experiment

In the case of the SCI patient, the training period was for fourteen days. Within this time frame the patient would come to the rehabilitation institution three times a week. Each of these sessions consisted of the patient sitting in an upright position and performing weighted dorsal and plantar flexion. The apparatus was interfaced with a PC in which the patient interacts with the VE. The goal of the VE was similar to the game "Snakes", where an avatar constantly moves forward while the user directs the direction in which the avatar goes. The VE was only utilized as a motivational tool for the patient to perform. It should be stressed that the purpose of this experiment was strength training rather than motor learning. The reason is to compare if there were any common trends between motor learning and the physical therapy. In both parts of the experiment (VE & SCI) the subject was instructed to perform a goal-oriented task. This often requires some control over the force generated by the muscle.

3.2.2 Surface EMG Measurements

The subject was required to perform a MVC on the initial day of the experiment (before training commenced) and the final day (after the experiment concluded). Disposable Ag/AgCl sEMG electrodes with diameter of 1 cm were placed on anatomical landmarks for the right and left tibialis anterior (TA). Although, the TA is a different motor group than the soleus, it has been demonstrated by Mochizuki et al. [56], that the motor units of the TA and soleus muscles are synchronous. Finally the EMG signal was sampled at 2 kHz and was bandpass filtered at 10 to 1000Hz After the signal was acquired, the same signal processing techniques in section 3.1.5 were applied.

Chapter 4

Results

4.1 Virtual environment training

4.1.1 Virtual environment performance

Throughout the experiment the subject did not experience any simulator sickness as described by previous studies [69, 70]. However, the subject did experience fatigue during days 2 and 4, in the soccer training. After day 4 of soccer training the subject experienced minimal fatigue throughout the training with the exception of days 9, 14 and 16. During those days, the subject did not receive sufficient amount of sleep the night before.

Test A: Basic Balance Test

Before the discussion of the VE performance, it should be noted that there exist gaps between certain days. For example the performance results in Test A consisted of the response time of each target. As can be seen from Figure 4.1 to Figure 4.2, there are gaps between certain days. These gaps are the result of the VE not selecting Test A for that day. In addition to the gaps, the second set of balance tests were assigned to day 19 because there were two sets of data assigned to day 18 and could not be displayed by the graphing software.

For Target 1 (Figure 4.1) and Target 2 (Figure 4.2) it was noticed that the response time showed a decrease. More specifically, the response time of Target 1 in the last session was 1.4 times faster than the

initial response time. Similar results were also found in Target 2; where the response time of Target 2 in the last session was 1.3 times faster than the first session.

Figure 4.1: The response time measured from the basic balance test (Test A) for the first target.

In Target 5 (Figure 4.3) there the results for days 2, 11, 18 and 19 were missing. This was a result of the subject not being able to complete this target in the allocated time. This may be due to the increase in difficulty throughout the test, and it is believed that if the experimentation was to continue, there would have been a decrease in response time.

Test D: Single Leg-Balance Test

The measured performance in Test D was evaluated on the subject's game score while standing on one leg. Although there was no documentation of how the game score was calculated, it was assumed that the value was derived from either the standard deviation of lateral movement and/or frequency at which the COP crosses the midline. After observing Figure 4.4, one may conclude that there was a slight increase in game score. The average of the initial three tests was taken and was compared to the performance on the last

Figure 4.2: The response time measured from the basic balance test (Test A) for the second target.

Figure 4.3: The response time measured from the basic balance test (Test A) for the fifth target.

three tests. This resulted in an increase of 4% between the respective days. Therefore, it can be concluded that the subject improved his balance throughout the course of the experiment.

Figure 4.4: Game score measured during the single leg balance test (Test D)

Soccer Training

As discussed, the soccer training was broken into two training sections. The first five days consisted only of training at the beginner difficulty level whereas the remaining days consisted of training at the advanced difficulty level. In both settings, the game score was recorded at the end of the training session. Figure 4.5 displays the game score at the beginner level with respect to session number. It can be seen that the figure exhibits a gradual increase in score as the user progresses through the training. A similar trend was noticed in the advance difficulty level (Figure 4.6). A linear fitting of both Figure 4.5 and Figure 4.6 resulted in a slope of 3.6 for Figure 4.5 and a slope of 1.9 for Figure 4.6. Intuitively, it can be suggested that the slope may be indicative of the difficulty level of the training.

Figure 4.5: Soccer game score with respect to session (at beginner difficulty)

Figure 4.6: Soccer game score with respect to session (at advance difficulty)

4.1.2 Changes in %DET throughout testing and training

Test A: Basic Balance Test

During Test A there were two points of view in which %DET was utilized to observe the muscular system. The first point of view was to compare %DET while the subject attempted to shift his weight to the virtual target (dynamic contraction) and when the subject is holding his position (sustained contraction). Figures 4.7 through 4.11 present the %DET of dynamic contraction and sustained contraction as a function of days for the RPL. It was not possible to ascertain the dynamic portion of the EMG data during Target 1 and Target 2 on day 12 as the subject was not able to get into position before the response time initiated. This resulted in the analysis of %DET only for sustained contraction.

Figure 4.7: Comparing the %DET of dynamic contraction (blue) and sustain contraction (red) in the RPL muscle during basic balance test (Test A) for target one.

It was noticed for the Right Peroneus Longus (RPL) muscle that the general trend between day 17 and day 19 (last session: day 18) was a gradual decrease in %DET. This same decrease existed in Target 1 and Target 2 for days 8 to 9 and 11 to 12. On the other hand, during days 17 and 19, it was observed that there were elevated levels of dynamic contractions. However, these elevated levels of dynamic contractions do

Figure 4.8: Comparing the %DET of dynamic contraction (blue) and sustain contraction (red) in the RPL muscle during basic balance test (Test A) for target two.

Figure 4.9: Comparing the %DET of dynamic contraction (blue) and sustain contraction (red) in the RPL muscle during basic balance test (Test A) for target three.

Figure 4.10: Comparing the %DET of dynamic contraction (*blue*) and sustain contraction (*red*) in the RPL muscle during basic balance test (Test A) for target four.

Figure 4.11: Comparing the %DET of dynamic contraction (*blue*) and sustain contraction (*red*) in the Right Peroneus Longus muscle during basic balance test (Test A) for target five.

not appear evident in Figure 4.9 and Figure 4.10. Instead, Targets 3 and 4 appear to reach an equal state between the %DET of dynamic and sustained contractions.

As previously mentioned, there were two sets of electrodes which were employed. The results from these two sets are analyze separately in order to remain consistent. It should be noted that the majority of the observations in this section were measured using the 3M™ Red Dot™ electrodes.

Figure 4.12: Comparing the %DET of dynamic contraction (*blue*) and sustain contraction (*red*) in the RS muscle during basic balance test (Test A) for target three.

Now switching to the analysis of the Right Soleus (RS) muscle, it was seen that %DET for Target 3 (Figure 4.12) and Target 4 (Figure 4.13) on days 18 and 19 had changed with respect to RPL. During the RPL measurement, Target 1 and Target 2 developed a notable increase in dynamic contraction. However in the RS case, Target 3 and Target 4 exhibited a similar promotion of dynamic contraction rather than Targets 1 and 2. In fact, Target 1, Target 2, and Target 5 did not demonstrate any discernable trend at all and can be view in Appendix B.

The decrease in %DET for the majority of the targets in RPL had appeared in some of the %DET

Figure 4.13: Comparing the %DET of dynamic contraction (blue) and sustain contraction (red) in the RS muscle during basic balance test (Test A) for target four.

measurements in RS. More specifically, there was a gradual decrease between days 8 to 12 and 17 to 19 for Targets 3 and 4. Both muscles were subjected to a decrease in %DET during the last days of testing. It is interesting to note that the decrease in %DET was observed during the use of both sets of electrodes. Although it is not currently apparent, it is hypothesized that this decrease may be related to motor learning. More details are discussed in Chapter 5.1.1.

Though not as significant as the first point of view, the second set of analyses consisted of the %DET for the entire contraction period in each target. This second set of analysis gives an overall view of the dynamics of the contraction as the subject completes a target. After the examination of the results from this point of view, the emergence of a common decreasing trend was observed. This decreasing trend could be seen in Figure 4.14 and is also apparent in the rest of the targets ¹.

¹Appendix C

Figure 4.14: Comparing the %DET of RS (blue) and RPL (red) muscles during basic balance test (Test A) for the first target.

Test D: Single Leg-Balance Test

Finally, the last test which the %DET analysis was applied to was Test D. As previously mentioned, the initial, mid and last two seconds of the contraction were utilized. Figure 4.15 to Figure 4.17 displays the results of the %DET for both RPL and RS muscles. For the duration of the initial contraction (Figure 4.15), the RPL %DET shows evidence of a general decrease from days 13 to 18. Conversely, between days 14 to 17 (Figure 4.15), the RS %DET levels display a general increase in %DET. Nevertheless during the last day of Test D, the %DET levels reach its lowest level. Once again, this decrease had exhibited itself throughout the single leg balance test. It was shown that the last three trials (17 to 19) of the game score demonstrated a more consistent value than the prior three game score (13 to 16). It is hypothesized that this decrease in %DET may be related to a decrease in fluctuation of force. Yao et al. [24] demonstrated that as motor unit synchronization increases, there is an increase in fluctuation of force. Therefore, a decrease in motor unit synchronization may suggest an increase in performance of single leg balance.

Another phenomenon which can be seen in Figure 4.15 to Figure 4.17 was the elevated levels of %DET in the RPL muscle on days 14 and 16. This phenomenon was present in the three time periods of the analysis

Figure 4.15: Comparison of %DET for RS (red) and RPL (blue) muscle during the first two seconds of the single leg balance test (Test D)

Figure 4.16: Comparison of %DET for RS (red) and RPL (blue) muscle during the midway point of the single leg balance test (Test D)

Table 4.1: Change in %DET between days 13 and 18

Contraction	Δ %DET Trial 1	Δ %DET Trial 5	Δ %DET Trial 10
Initial	-2.354	-1.389	-1.884
Final	-1.167	-1.036	-1.658

Table 4.2: Change in %DET between Initial and Final contractions

Contraction	Δ %DET Trial 1	Δ %DET Trial 5	Δ %DET Trial 10
Day 13	1.170	-1.119	1.430
Day 18	2.362	1.198	1.713

during the Test. However, these elevated levels appeared to dissipate during the final three sessions (with the exception of the last contraction on day 17). Although it is more apparent in Chapter 4.1.4, the dissipation of the elevated levels of %DET in RPL muscle may be due to a convergence phenomenon.

Soccer Training

To assist in the development and improvement of the above tests, a soccer training VE was employed. Figure 4.18 depict the initial two seconds of the first contraction in the RS muscle, whereas Figure 4.19 depicts the initial two seconds of the last contraction in the RS. Similar to most of the tests in this experiment, there was a gradual decrease in %DET between day 13 and day 18. Table 4.1 depicts the factor in which %DET changes between these days for both time frames.

After some observations, it appeared that the initial contraction for Trial 1 decreased by a factor of 2.35 between the observed days. This was the largest deviation to the other trial sessions and contractions. The second largest deviation occurred during the last trial under the same contraction window. Lastly, there appears to be little change in factors within the final contraction window.

Focusing on the time frame of days 13 to 18 with the exception of days 15 & 16, it was observed that the mid-trial (Trial 5) %DET was more prominent relative to the initial and final soccer sessions. This heightened state was also believed to be the result of fatigue because of the limited amount of rest periods given between Soccer Trial 1 to Trial 5. Once Trial 5 was over, a longer rest period was given. Additionally,

it has been previously stated that an increase in %DET is directly related to fatigue. Heightened levels of %DET also resided in Figure 4.19 compared to Figure 4.18. Table 4.2 tabulated the deviation between the initial contraction and the final contraction for each of the specified trial sessions.

4.1.3 Changes in RMS and MNF throughout testing and training

Test A: Basic Balance Test

There were several trends which occurred throughout the experiment for both RMS and MNF. Figure 4.20 displays general RMS trend. In this figure, there appeared to be a decrease in overall amplitude between days 8 & 12 and days 17 & 18.

In terms of the change in MNF, there was a gradual increase in frequency as the subject progressed through the experiment (Figure 4.21). This increase was evident in both sets of electrodes and muscles. Unlike the %DET analysis, there does not appear to be a distinct difference between the MNF of the burst and sustained contractions.

Test D: Single Leg-Balance Test

Figure 4.22 shows that the RMS gradually increased during days 13 to day 16 for the RPL muscle. However, a decrease in RMS values was exhibited in the following days. In terms of the RS muscle, this increase occurred up until day 17 and then on day 18 there was a decrease in value.

Observation of MNF during Test D (Figure 4.23) for both muscles did not show a consistent trend. However, there was an increase in MNF during the last day of testing relative to days 13 to 17.

4.1.4 Time course of %DET during testing

Up until this point, the %DET analysis has been taken at a specified point in time. In signal processing terms, this process is similar to taking an average within a window. Under certain circumstances, this sample may not be enough to estimate what is occurring in the signal of interest. A moving average might be useful

Figure 4.17: Comparison of %DET for RS (red) and RPL (blue) muscle during the last two seconds of the single leg balance test (Test D)

Figure 4.18: The first two seconds of the %DET for Soccer Trial 1 (blue), Trial 5 (green) and Trial 10 (red)

Figure 4.19: The last two seconds of the %DET for Soccer Trial 1 (blue), Trial 5 (green) and Trial 10 (red).

Figure 4.20: Comparing the RMS of dynamic contraction (blue) and sustained contraction (red) in the RPL muscle during basic balance test (Test A) for target one.

Figure 4.21: Comparing the MNF of dynamic contraction (blue) and sustained contraction (red) in the RPL muscle during basic balance test (Test A) for target one.

Figure 4.22: Comparison of RMS for RS (red) and RPL (blue) muscle during the first two seconds of the single leg balance test (Test D)

Figure 4.23: Comparison of RMS between RS (red) and RPL (blue) muscle during the first two seconds of the single leg balance test (Test D).

in such circumstances. Similar to the concept of a moving average filter, a specified window length is required to slide across the signal of interest to compute the %DET as a function of time. The window length during this analysis was kept at 2 seconds (1600 points). The overlap between each sliding window was selected to be 75% of the window length (400 points).

This process was applied to day 14 and day 18 of Test D. As previously mentioned, day 13 suffered data loss from the wireless system. As a result the following day was used in this analysis. Figure 4.24 depicts the time course of %DET for the RPL muscle. During day 14 the mean value was calculated to be 71.47 with a standard deviation of 10.71. Meanwhile, it was observed that the mean value was 23.95 with a standard deviation of 9.454 on the last day of testing. Figure 4.26 shows a slight decrease in standard deviation between the periods of interest.

Figure 4.27 compares the same time periods as Figure 4.28, but with the RS muscle. This resulted in a significantly different change between the training days with respect to the RPL muscle. Day 14 and day 18 resulted in similar mean values (28.86 and 28.2). However, day 14 possessed a standard deviation of 10.9,

Figure 4.24: The %DET time course from Day 14 (blue) and Day 19 (green) test session of single leg balance for the RPL muscle.

Figure 4.25: Mean and standard deviation values from time course of %DET for RPL muscle

Figure 4.26: Mean and standard deviation values from time course of %DET for RS muscle

Figure 4.27: The %DET time course from Day 14 (blue) and Day 19 (green) test session of single leg balance for the RS muscle.

Figure 4.28: Comparing RPL (blue) and RS (green) muscles with respect to %DET time course during Day 14 of the single leg balance test (Test D).

Figure 4.29: Comparing RPL (blue) and RS (green) muscles with respect to %DET time course during Day 19 of the single leg balance test (Test D).

whereas Day 18 possessed a value of 5.207. As can be observed in Figure 4.25 & 4.26, there also appears to be a decrease in standard deviation as the subject progresses through the last week of training.

Alternatively, by comparing the two muscles against each other with respect to the time, the convergence of %DET for both muscles was observed. Figure 4.28 displays the significant difference between the RS and RPL on day 14. However by the second session of day 18 (Figure 4.29), both levels of %DET were within the same range ².

4.1.5 Time course of RMS and MNF during testing

Applying the same concepts as the time course of %DET, a sliding RMS and MNF window was implemented. The result was a time course of RMS and MNF which can provide some information on the changes in the muscle during a session. For both RMS and MNF, an overlap of 75% of the window size was instituted for both algorithms. Similar to the methods described in the above sections, the time courses were calculated for Test D for days 14 to 18.

If one compares the change between day 14 and day 18, one sees that there was a decrease in mean RMS value for the RPL muscle (Figure: 4.30). More specifically, the mean RMS value on day 14 was calculated to be 0.119 and drop to 0.0288 by day 18. Conversely, the MNF increased from 73 Hz on day 14 to 123.1 Hz on day 18. However, there was no distinct difference between day 14 and day 18 for the RS muscle. Statistically, the means for both RMS and MNF were tabulated to be 0.74 and 115.3 Hz respectively, during the initial time frame. These values did not change significantly by Day 18 (RMS=0.0353, MNF=113.40). This lack of change in mean level (with respect to the RPL) also occurred during the time course of %DET for the RS muscle. However, the standard deviation was found to decrease throughout the last week of the experiment. In the case of RMS and MNF, the standard deviation was seen to have large values during day 16 and day 17 (Figure 4.31 to Figure 4.34). Nevertheless, the other days revealed consistent standard deviation between the observed days. This was not the case for the RPL muscle as it appeared that both the RMS and MNF standard deviation showed decreases in values.

²The entire transition from day 14 to day 18 can be seen in the Appendix D

Figure 4.30: Comparing the RPL muscle RMS time course between Day 14 (blue) and Day 18 (green) during the single leg balance test (Test D).

Figure 4.31: Mean and standard deviation values from time course of RMS for RPL muscle

Figure 4.32: Mean and standard deviation values from time course of RMS for RS muscle

Figure 4.33: Mean and standard deviation values from time course of MNf for RPL muscle

Figure 4.34: Mean and standard deviation values from time course of MNf for RS muscle

Figure 4.35: Comparing the RPL (blue) and RS (green) muscle with respect to RMS time course during Day 14 of the single leg balance test (Test D).

Figure 4.36: Comparing the RPL (blue) and RS (green) muscle with respect to RMS time course during Day 19 of the single leg balance test (Test D).

Figure 4.37: Comparing the RPL (blue) and RS (green) muscle with respect to MNF time course during Day 14 of the single leg balance test (Test D).

Similar to the time course of %DET, the RMS and MNF time course of both RPL and RS were plotted. The change between these characteristics throughout training can be seen in Figure 4.35 & Figure 4.36 (RMS) and Figure 4.37 & Figure 4.38 (MNF). In both instances, the RPL and RS levels begin to converge towards each other. As a result, the distance between the two signals had decreased. Figure 4.43 depicts the average distance between RPL and RS for each time course.

4.1.6 Motion artifacts

Several of the measured EMG data were plagued with motion artifacts. These led to high levels of %DET (90% - 100%). Figure 4.40 and Figure 4.41 represent the %DET during soccer training for days 8 to 12. As Figure 4.40 illustrates the entire %DET measurement was above 90%. It should be noted that during the latter half of the training the EMG signal had been saturated due to movement. Therefore, it can be shown that there is a correlation between motion artifacts and the abnormally high %DET values. Although the %DET values are slightly lower in the initial contraction, the %DET was still above the 90% level (except for the last two days). These escalated values of %DET between Figure 4.40 and Figure 4.41 may be due to muscle fatigue.

Motion artifacts were not only limited to the soccer training but also in Test A. Observations in Test A figures show that the %DET had surpassed the 90% level on multiple occasions. It was also interesting to note that these values only occurred during the dynamic contractions portion of the movement. As a result, it can be assumed that values of 90% or greater have some relationships with motion artifacts. Evidence which supports this theory was the fact that during the single leg balance test, the %DET did not reach this elevated state. This may be due to the fact that the movement of the limb was negligible compared to the movement that is required for the soccer training and Test A.

4.1.7 Issues and adjustments

One of the initial problems that occurred during the course of the experiment involved the Biocapture® system. The device was set to an amplitude range of ± 25 mV during the initial five days of training. This resulted in a significant decrease in the signal-to-noise ratio and led to the elimination of EMG data from those days. The amplitude range was then lowered to a setting of ± 3 mV thereafter.

Figure 4.38: Comparing the RPL (blue) and RS (green) muscle with respect to MNF time course during Day 19 of the single leg balance test (Test D).

Figure 4.39: The averaged normalized distance between the time course RMS (Blue), MNF (Green), %DET (Red) data of RPL and RS.

Figure 4.40: Occurrence of motion artifacts during the last two seconds of soccer training for the RS muscle. (Trial 1 (blue), Trial 5 (green) and Trial 10 (red))

Figure 4.41: Occurrence of motion artifacts during the first two seconds of soccer training for the RS muscle. (Trial 1 (blue), Trial 5 (green) and Trial 10 (red))

Table 4.3: Average distance between Left TA and Right TA (before and after training)

Method	Pre-Training	Post-Training
RMS	0.248	0.191
MNF	2.278	33.564
%DET	4.195	55.253

In addition, the sampling rate was also adjusted after the tenth day from 769 Hz to 800Hz. Although the device appeared to have the capability of sampling at 980Hz, the wireless signal dropped a significant portion of the EMG measurement at that sampling rate. Unfortunately this problem occurred on the thirteenth day during Test D although the sampling rate was set to 800 Hz. The final ten seconds of data had been lost due to dropping of packets, in the wireless receiver.

The electrodes, which were attached to the subject, were changed on the 13th day. It was observed that the initial set of electrodes (MVAP-II) were sensitive to motion artifacts. This resulted in higher levels of %DET during the initial days of the experiment. It is believed that this heighten level may have effected the sensitivity of the analysis. As a result, the majority of the observations only focused on the second set of electrodes.

Lastly, there was a significant number of motion artifacts within the EMG data. This was prominent in a majority of the soccer training sessions. More of the effects of the results-of-motion artifact are discussed in the latter part of this chapter. Consequently, the electrodes were changed on the thirteenth day to improve the signal to noise ratio and therefore the comparison of both sets will not be made.

4.2 Spinal Cord Injury Patient

4.2.1 Time Course of Spinal Cord Injury Patient

Since only the maximum voluntary contraction (MVC) of the SCI patient was available, the natural choice of analysis was the time course of RMS, MNF, and %DET. By employing the %DET analysis there were two distinct trends noticed during MVC of the tibialis anterior(TA) muscle. In the right TA, it was observed that there was a decrease in %DET between pre-training (mean 79.49) and post-training (mean 20.73).

Additionally, both %DET time courses experienced an increase in level as time progressed, which is indicative of muscle fatigue. On the other hand, the left TA did not experience a significant decrease in %DET unlike the right TA. It was observed that the mean %DET during pre-testing was calculated to be 81.57 as opposed to 75.98 post-training. Furthermore, the change in %DET with respect to time before and after training was affected. During the pre-training measurement, it was demonstrated that there was an increase in %DET near the end of the MVC. However, post-training displayed a decrease in %DET near the end of the MVC.

Figure 4.42: Comparing the %DET time course of the SCI patient's right TA; pre-training (blue) and post training (green)

Switching to the more traditional analysis, it was noticed that both TA (left and right) RMS values decreased after training. More specifically, the left TA at pre-training was 0.657 and decreased to 0.303 post training. The RMS value for the right at pre-training was calculated to be 0.906 and decreased to 0.111. In terms of MNF, both TA muscles showed signs of an increase in the spectrum. The right TA demonstrated a more notable increase in frequency with a change in MNF of (pre) 85.86 Hz to (post) 122.6 Hz. However, similar to the change in %DET, there was not as much of a significant change of MNF between pre-training (mean 85.71) and post-training (mean 89.02).

Figure 4.43: Comparing the %DET time course of the SCI patient's left TA; pre-training (blue) and post training (green)

Similar to Test D, the absolute difference was calculated for each time course method. It was observed, from Table 4.3 that both MNF and %DET increased in value. On that other hand, there was a slight decrease in value in RMS. More details regarding this trend will be presented in the next chapter.

Chapter 5

Discussion

5.1 Virtual environment training

5.1.1 Performance Vs. %DET

The most notable indication of improvement in performance was demonstrated during the soccer training. It was clearly seen that, as the subject progressed through the training, the game score would increase. Concurrently, the %DET measurement demonstrated a gradual decrease in the first two seconds of both the initial game and final game.

The single leg balance test (Test D), resulted in the second most notable change in %DET during training. It was observed that the numerical scores did not demonstrate a gradual improvement during the course of the experiment. However, the last three trials demonstrated reduced variation in game score compared to days 14 through 16. It is known that the COP is directly related to both the ankle muscle activity and the resulting force which is produced [71]. If there were to be large fluctuations in force, then they would affect the ability of the CNS to maintaining a stable COP and centre of mass (COM). Simulations by Yao et al. [24], have shown that an increased fluctuation of force is directly related to increase in motor unit synchronizations. This would then suggest that the improvement of stability in the single leg balance test is indicative of a decrease in synchronization. As a result, the decrease in %DET, as seen in the single leg balance test, complements the simulation by Yao et al. [24] quite nicely.

Although this experiment utilized two different electrodes, Test A had demonstrated that both sets of

data exhibited a decrease in %DET. This decrease was more prominent on days 8 to 12, as there were more data.

Overall, there exists a gradual decrease in %DET during both training and testing. This finding supports the result of Liu et al. [8] where the average %DET decreased before and after physical therapy. It has been suggested by Liu et al. [8] that %DET may be sensitive enough to detect, "developing fatigue, tremor, or even pathological condition." One possible addition to this hypothesis could be a relationship between %DET and viscoelastic force. It has been suggested that the CNS heavily relies on viscoelastic forces during the initial learning stage. This is due to a poor internal model and as learning progresses, this model would become more influential, while viscoelastic forces become less so [72]. Osu et al. [72] demonstrated that there is a decrease in viscoelastic force after long term training. This may explain the significant decrease in %DET during training and testing seen in the soccer training and Test D.

Another possibility for the decrease in %DET throughout the experiment may be directly related to the vestibulospinal pathways. The vestibulospinal pathways are where the lateral vestibular nucleus descends to the alpha motoneuron pools where they are innervated to the gastrocnemius and soleus [73]. It has been suggested that these bilateral pathways could produce motor unit synchronization during postural tasks such as balance or quiet stance [56, 37, 73]. Based on this, it may be theorized that the decrease in %DET is associated with a decrease in the reliance of the vestibular system (sensory peripheral). As previously mentioned by Halsband et al. [16], the automation of movement occurs during the late phases of motor learning. Other evidence which supports this result can be seen in the Boostra et al. [37]. The Boostra et al. [37] study was similar to that of Mochizuki et al. [56], but with the addition of the consumption of alcohol by the subject. It is known that being intoxicated reduces motoneuronal excitability, which would impair sensory peripherals [37]. As a result, this study also showed that synchronization of motor units decreases after the consumption of alcohol. On the other hand, this seems to be somewhat contradictory as Mochizuki et al. [56] suggested that the bilateral soleus motor unit would become more synchronous when the eyes are closed. However, the Mochizuki et al. [56] study did not find a significant difference in synchronization of motor units between open eyes and closed eyes.

5.1.2 Performance Vs. Traditional methods

Recently, a method known as joint analysis of EMG amplitude and spectrum (JASA) has shown evidence that there may be a relationship between force and EMG signals [74]. However, this contradicts the finding of Farina et al. [75] where there is no relationship between muscular force and EMG spectrum. Nevertheless, if one were to make the assumption JASA was a valid measurement then the following is true¹

1. Force increases when amplitude and mean frequency increases.
2. Force decreases when amplitude and mean frequency decrease.
3. Fatigue occurs when amplitude increases, but mean frequency decreases.
4. Recovery occurs when amplitude decreases and mean frequency increases.

When applying these sets of rules to this experiment, it was observed that during the course of Test A and Test B, there appeared to be a general decrease in amplitude and an increase in MNF. If one were to also take into account the soccer results and the fact that there is an inverse relationship between %DET and MNF, then the subject would also be considered to be in recovery (JASA). Since all balance test were performed at the beginning of the experiment it is hypothesized that the recovery stage could also be a measure of motor learning.

5.1.3 Time courses

In past studies [23], it has been demonstrated that the EMG magnitude becomes less variable while practising a new task. In the case of the work of Gabriel et al. [23], the measure of variability was calculated as the standard deviation of the EMG divided by the mean, and the result was multiplied by one hundred. Applying this same calculation to the RS muscle in Test D, it was shown that there was a decrease in variability (Table 5.1).

¹It has been previously mentioned that MNF is more reliable than MDF[34]. As a result this experiment used MNF rather than MDF.

Table 5.1: Variability

Days	Day 14	Day 15	Day 16	Day 17	Day 18	Day 18F
Variability	80.591	70.859	78.817	105.495	73.309	76.410

Based on the dataset presented in Table 5.1, it is hypothesized that there is a relationship between the synchronization of motor units and the magnitude of EMG variability. If this hypothesis is true, then the decrease in variability may be due to a more consistent firing of motor unit pairs. By observing the results presented in Table 4, it can be seen that the standard deviation of the %DET decreases during the course of the experiment. This would intuitively mean that the synchronization of motor unit pairs would be firing more consistently, which then would lead to a reduced variability of the EMG signal. The reduction of variability was found in the study by Gabriel et al. [23], where subjects practise an upper arm movement. As a result, the standard deviation of %DET time course would complement the findings of [23].

Comparing the two different methods, it appears that the RQA proved to be more sensitive than the variability measurement. As Table 5.1 shows, the variability on day 17 had produced a large value. This anomaly does not conform to the trend that was described in the previous work [23]. If there were to be a larger data-set in this experiment, than this anomaly may not have been as apparent. Since evaluation of EMG signals should not be based on the magnitude of the signal. The locations of the electrodes have a significant relation to the variations in the EMG signals. Consequently, motion artifacts may also have a factor in the variability of the EMG signal. As a result, if there were a large data-set, the motion artifacts could be averaged out. On the other hand, the standard deviation of the %DET time course seem to be more resilient to these factors (with the exception of motion artifacts). This could be due to the way the RQA is calculated. More specifically, this algorithm uses the signal itself, which evades the restrictions of linearity, stationarity, etc.

A similar comparison can be made between the variability measurement and the RMS and MNF time courses. In both instances, Day 17 exhibited elevated levels of either variability (Table 5.1) or standard deviation with respect to the other testing sessions. At the same time, there did not appear to be any discernable trend that evolved in the standard deviation of the RMS time course. On the other hand, it was noticed that the standard deviation of the MNF time course experienced an increase in value until the last day of testing. This result was unexpected since several studies have shown that there is a relationship

between MNF and %DET. It should be stressed that the traditional Fourier Transform often requires a stationary signal. This may result in several periods in which the sliding of the window, in which the signal is non-stationary, would lead to an invalid result.

The second assessment of the time course was the tabulation of the convergence of RS and RPL muscles with respect to the %DET, MNF and RMS. By plotting this convergence it was observed that the decay of absolute distance appeared to be exponential-like (Figure 4.39). This function has been demonstrated by Newell et al. [33] to be one of the possible trends that occur during motor learning. The rationale behind this type of learning curve is when the subject practises a task more and more, the rate of learning systematically decreases due to the biological system limit [33]. Based on the above, there is strong evidence that the subject in this study demonstrated motor learning during training, which suggests that the convergence time course analysis may be a useful tool in assessing motor learning.

On the other hand several studies have shown that the power law learning curve has been the predominate function of motor learning [33]. The power law is estimated by dividing the difference in consecutive errors by the value of the error at the trial. Unfortunately, the method in which data was collected did not provide the experimenter direct access to the error in performance. However, the goal of the power law is to observe in the change both the error and rate of error. This can also be observed using the convergence tabulation. In fact, the convergence seen in %DET (Figure K.3) appears to be similar to the power law function seen in Newell et al. [33].

5.1.4 The influence of fatigue

The most prominent phenomenon in any physical activity is the development of fatigue. There is a substantial amount of evidence that demonstrate the relationship between motor unit synchronization and fatigue. Consequently, this phenomenon had also arose in this experiment. The soccer training had the most notable instances of fatigue, as it was more demanding than the other tests. It can be seen from Figure 4.18 that trial 5 often had the largest %DET during the respective days. The exception was on days 15 and 16 where the largest %DET occurred during the last game.

The influence of fatigue was also notable within each game. It was seen that Figure 4.19 displays a more enhanced %DET relative to Figure 4.18. This suggests that this enhancement is due to fatigue and is in

agreement with previous work. However, the influence of fatigue was not as prominent during the balance tests. This may be due to the fact that the soccer training was more strenuous compared to the balance tests. In past studies, the experimental protocol, which leads to the progression of fatigue, often contained a weight or load. As a result, the %DET measured during the balance test may be indicative of motor unit synchronization with respect to motor learning.

Aside from the decrease in %DET as a result of fatigue, it was observed during Test D that the standard deviations of %DET were higher compared to the other days. Although this will require further investigation, the standard deviation of %DET may be an alternative method for measuring fatigue. The disadvantage of this method compared to simply calculating the %DET is that the time course of %DET requires a large data set. As a result, this method would not be effective during short dynamic contractions.

5.1.5 The occurrence of motor strategies

As subjects become more aware of their direction and the extent of their error, it has been suggested that they begin to pre-plan their movements [60]. One of the indications of this pre-planning process is a shift in muscle activity between muscles. This shift is believed to be related to the optimal performance of the subject. By observing Test D, it can be seen that there appears to be an adjustment in the activity between the RS and RPL muscles (Figure 4.15). More specifically, it appears as though there may be an inverse relation between the RS (increasing trend) and RPL (slight decreasing trend) during day 14 to day 17. This may depict a shift in muscle activity between the peroneus longus and soleus which was similarly described in Betker et al. [60]. On the other hand, this equalization of both the RS and RPL muscles during the latter days of the experiment may provide evidence that the central nervous system (CNS) was increasingly simplifying the control of the muscles. It has been suggested by Shemmell et al. [76] that after practice, the activation of synergistic muscles will become similar. By observing the results in Test D, one could suggest that both the RS and RPL evolved to a synergistic state. In the case of Shemmell et al. [76], it was demonstrated that there was a reduction in activation pattern of EMG data. This could also explain the reduction in %DET experienced during the last three days of testing.

During days 15 (Figure D.2) and 16 (Figure D.3), it was observed that the %DET approached similar values near the end of the testing. By day 17, the majority of the levels were within the same range and

would continued until the last day of testing. The convergence of the %DET for their respective time periods was observed in Table 4.3.

The same trend was also depicted for the RMS and MNF time courses. The difference between the distances of the traditional time course and RQA was the presence of increased levels during Day 16. This may be due to fatigue effects experienced during that day. Nevertheless the trends observed during the traditional time course and %DET time course may provide evidence supporting the hypothesis of Shemmell et al. [76] on the simplification of the central nervous system.

5.1.6 Omitted balance tests

As previously mentioned, there were five possible balance tests which the subject could have been required to performed. The two main tests that was described in the Chapter 4 was the basic balance test and the single leg balance test. The other three tests were a walking test, steadiness test, and agility test. Unfortunately, both the walking test and steadiness test could not produce any usable sEMG signal. As a result, both tests were not considered in this experiment.

Although the sEMG signal for the agility test (Test B) were usable, there was not enough data to distinguish a trend. As a result, the performance/%DET, RMS and MNF analysis is left in Appendix G, Appendix H, Appendix I, respectively.

5.2 Spinal Cord Injury Patient

5.2.1 Assessment of SCI Patient

Although the SCI patient was subjected to physical exercise rather than VE motor training, both experiment resulted in a decrease in %DET. This trend appears to be common in lower back pain patients described in Liu et al. [8] who exhibited a similar decrease in %DET after physical exercise. However, due to differences in the two experiments there should also be some discrepancies between them. One particular example was seen in Figure 4.43 where the time course of %DET increased during pre-training, but transformed into a

decreasing trend post-training. This may be indicative of the patient developing a resistance to the fatigue [8]. Another example that demonstrated a divergence in the results between the two experiments was the decrease in standard deviation during Test D. This decrease did not occur during the MVC for the patient as the right TA experienced an increase in standard deviation while the left TA remained consistent (pre and post training).

In terms of the more traditional analysis, it was observed that the RMS value decreased, while the MNF increased after training. As previously mentioned, this trend was inductive of recovery based on JASA [74]. This recovery classification also existed during the VE training, where RMS also decreased and MNF increased as a result of testing and training. In terms of strength training, the JASA method classified the muscle of interest as recovering from fatigue. This suggests that the patient may be more resilient to fatigue after training. As a result, the recovery classification could be more related to strength training rather than motor learning.

Considering the above observation, the respective time course analysis resulted in the patient showing some signs of improvement over the course of training. More specifically, the patient was less affected by fatigue after training than prior to training. This would be the expected result after strength training for a long period of time. In terms of the RQA, the decrease in %DET may be indicative of the reduction of fluctuation in force produced by the muscle. In both the SCI patient and the VE subject a decrease in %DET was demonstrated. This may be due to an increase in control of force for both subjects. Additionally, it can be suggested that the right lower limb may require some more training as a result of elevated standard deviation of %DET.

Chapter 6

Conclusion

Virtual rehabilitation has grown significantly in the past decade. As technology advances, commercial video gaming consoles will become more interactive and cost effective. Applications of these consoles may play a larger role in assisting patients who seek rehabilitation in their homes.

The purpose of this case study was to determine the possibility of the utilization of RQA to quantify motor learning in a virtual environment. Based on the experimental results on a control subject, a method was proposed in order to assess motor learning, which may have shed some light on motor strategies that occur during the learning process.

The experiment consisted of the utilization of a commercially available video gaming console in order to train and test a subject's motor abilities. The subject was required to perform two random tests (out of a possible five) and trained in a soccer simulator for three weeks using the Nintendo Wii® console and Wii Fit® software. EMG signals and game scores were acquired in order to assess the subject performance. Traditional EMG analyses were employed on the EMG signals and compared with RQA. During traditional EMG analysis, it was found that the root mean square value decreased as training progressed. Concurrently, the MNF appeared to shift to a higher frequency throughout training. Applying the JASA method, this trend is indicative of a recovery phase for muscles. Unfortunately, there were some instances where traditional analysis proved to be ineffective in assessing motor learning. It has been previously suggested that the reason for this unsuccessful application of traditional methods may be due to the requirement of stationarity. Where one method appeared to be ineffective, the other appeared to be effective. In a majority of the physical

activities, RQA demonstrated a heightened sensitivity to change in muscular activities. In this study, %DET demonstrated a decrease in value as the subject trained over the course days. It was hypothesized that this may be due to either a decrease in fluctuation of force or a decrease in the reliance of sensory peripherals, where both are based other studies. As a result, the combinations of both methods may be a useful tool in detecting motor learning. More specifically, the time course analysis for the respective methods exhibited trends. This may provide more information than the change in the instantaneous amplitudes. The two specific trends that surfaced during the VE training and testing, were a convergence of signal amplitude and a decrease in standard deviation. Both these trends may provide evidence, which is indicative of the simplification of the CNS in the control of muscles. Therefore based on the above results, it is hypothesized that a decrease in %DET occurs during motor learning for both individual muscles or a group of muscles. When comparing a group of unilateral muscles, it was observed that there was a convergence of %DET.

After extensive analysis of EMG signals collected from VE training, RQA and traditional analysis were applied to a patient who suffers from an incomplete spinal cord injury. The EMG signal was taken pre-training and post-training during MVC. The result of the traditional analysis demonstrated a decrease in RMS value while the MNF shifted to the right (higher frequencies). Once again, applying the JASA rule of thumb, it was observed that the patient was in the recovery period. In tandem with this result, %DET displayed a decrease in value after training. As a result, both experiments demonstrated similar trends during training and is hypothesized to that the change in %DET could be correlated to motor learning.

It is interesting to note that in both cases, the muscles of interest were classified as recovering when JASA is applied. Based on this result, it may be possible that the recovery category can extend its definition to include motor learning. Further experimentation is needed to determine if this category is more sensitive to strength training or motor learning tasks. In addition to this, JASA could also embrace the use of RQA in its analysis in order to provide a more robust method in assessment of muscles.

One possible application of this the RQA may be the evaluation of various rehabilitations programs which could be directed to patients who suffers from stroke, Parkinson's disease, etc. It is believed that an assessment tool such as the presented method may provide valuable information towards the recovery process of patients who suffer from these life-changing conditions. If a particular rehabilitation program may not be as effective, a change in training could be adjusted to increase the rate of recovery.

6.1 Future Work

The next step in this work would be to apply this method to patients who suffer from different conditions. More specifically, stroke patients who have lost some mobility in their limbs may be a good starting point to apply RQA. It would be interesting to see the progression of %DET during a patient's rehabilitation training alongside with the traditional methods of EMG analysis. Based on this work, it can be suggested that the %DET of the muscle of interest may decrease during the progression of the training. Additionally, with the use of the JASA method, the RMS and MNF may be characterized as the recovery phase as training progresses.

Although nearly complete, a custom software which interfaced with the Wii Fit balance board would have been a useful in this experiment. The objective of this custom VE was to intersect the virtual targets that appear on the screen with the subject's COP (very much like the agility test). These targets were to appear at random or at predetermined sequences. The COP was calculated and mapped to a virtual sprite in the VE. There were two modes that the VE can be set to: either linear or rotated mapping of the COP data. During linear mapping, if the subject were to shift weight more to the left, than the virtual sprite will also move in the left direction. However in the rotated mode, the subject's virtual sprite would be rotated counterclockwise about the on-screen-centre point coordinate. In other words, if the subject were to shift weight more to the left, than the virtual sprite may move to the left-up direction. By rotating the mapped COP, the subject will be forced to compensate by re-learning the movement. By having access to the COP the experimenter could calculate the trajectory of the COP data and the error in the trajectory. The relationship between the error in trajectory and %DET will be left for future work in RQA and VE. This method was prominent in many previous studies, which have been mentioned throughout this work.

Lastly, the most prominent phenomenon in any physical activity is the development of fatigue. One of the assumptions made during this study was that %DET is directly related to motor unit synchronization of muscle fibers. This resulted in a "mini" experiment (not involving VE) which attempts to confirm the production of synchronization of motor units using independent component analysis and RQA. The same subject (from VE study) was required to perform elbow flexion. The goal of this activity was to stop the arm within a target area. For more details regarding this exercise refer to Gabriel et al. [23]. The differences between Gabriel et al. [23] and this mini experiment is the utilization of a multi channel electrode which

is similar to Nakamura et al. [77]. In Nakamura et al. [77], ICA analysis was employed on the acquired EMG signals. This same procedure was applied to the EMG signals used in this mini experiment. There were several outcomes which were observed from this mini experiment. In the first, when the %DET was between 40% and 60% the appearance of motor unit trains in the ICs was noticed. For example, in IC2 of Appendix R: Figure R.1, the MUAP trains consisted of time intervals 50 to 60, 140 to 150 and 195 to 205. A second set of MUAP trains in IC1 was seen in the intervals 100 to 125, 140 to 150 and 195 to 205. However, these MUAP appeared to dissipate when the %DET was above 60% or below 30%. Intuitively, this may suggest that when there is a high level of synchronization, the ICA has a harder time distinguishing MUAP (Appendix R: Figure R.5). On the other hand, this result could suggest that the CNS does not have to fire as many MUAP to produce the same force [37]. In terms of low amounts of synchronization (Appendix R: Figure R.10), it appears that there is less motor unit firing in the region of interest. Appendix R contains the rest of the contractions from this experiment and there corresponding %DET.

Unfortunately, there are a few cases where the above result did not apply. For example Appendix R: Figure R.9 did not display MUAP trains in its IC, even though the %DET was calculated to be 55.05%. Overall, this does show evidence that RQA has the ability to detect motor unit synchronization. However, more research will be required to confirm that there is indeed a relation between the number of MUAP seen in the ICA and the %DET.

In conclusion, there is strong evidence which demonstrates the effectiveness of RQA on motor learning in VE systems. This work gives rise to future studies for improving the assessment of motor learning or confirming the detection of motor unit synchronizations.

Appendix A

Game score in Test A

Figure A.1: The response time measured from the basic balance test (Test A) for the third target.

Figure A.2: The response time measured from the basic balance test (Test A) for the fourth target.

Appendix B

The %DET of dynamic and sustained contraction for each target in Test A for Right Soleus muscle

Figure B.1: Comparing the %DET of dynamic contraction (*blue*) and sustain contraction (*red*) in the RS muscle during basic balance test (Test A) for target one.

Figure B.2: Comparing the %DET of dynamic contraction (*blue*) and sustain contraction (*red*) in the RS muscle during basic balance test (Test A) for target two.

Figure B.3: Comparing the %DET of dynamic contraction (*blue*) and sustain contraction (*red*) in the RS muscle during basic balance test (Test A) for target five.

Appendix C

The %DET of contraction for each target in Test A

Figure C.1: Comparing the %DET of RS (*blue*) and RPL (*red*) muscles during basic balance test (Test A) for the second target .

Figure C.2: Comparing the %DET of RS (blue) and RPL (red) muscles during basic balance test (Test A) for the third target .

Figure C.3: Comparing the %DET of RS (blue) and RPL (red) muscles during basic balance test (Test A) for the fourth target .

Figure C.4: Comparing the %DET of RS (blue) and RPL (red) muscles during basic balance test (Test A) for the fifth target .

Appendix D

Progression of Time Course in Test D

Figure D.1: Comparing RPL (*blue*) and RS (*green*) muscles with respect to %DET time course during Day 14 of the single leg balance test (Test D).

Figure D.2: Comparing RPL (*blue*) and RS (*green*) muscles with respect to %DET time course during Day 15 of the single leg balance test (Test D).

Figure D.3: Comparing RPL (*blue*) and RS (*green*) muscles with respect to %DET time course during Day 16 of the single leg balance test (Test D).

Figure D.4: Comparing RPL (*blue*) and RS (*green*) muscles with respect to %DET time course during Day 17 of the single leg balance test (Test D).

Figure D.5: Comparing RPL (*blue*) and RS (*green*) muscles with respect to %DET time course during Day 18 of the single leg balance test (Test D).

Figure D.6: Comparing RPL (*blue*) and RS (*green*) muscles with respect to %DET time course during Day 19 of the single leg balance test (Test D).

Appendix E

Root Mean Square Analysis on Test A

Figure E.1: Comparing the RMS of dynamic contraction (*blue*) and sustained contraction (*red*) in the RPL muscle during basic balance test (Test A) for target two.

Figure E.2: Comparing the RMS of dynamic contraction (*blue*) and sustained contraction (*red*) in the RPL muscle during basic balance test (Test A) for target three.

Figure E.3: Comparing the RMS of dynamic contraction (*blue*) and sustained contraction (*red*) in the RPL muscle during basic balance test (Test A) for target four.

Figure E.4: Comparing the RMS of dynamic contraction (*blue*) and sustained contraction (*red*) in the RPL muscle during basic balance test (Test A) for target five.

Figure E.5: Comparing the RMS of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target one.

Figure E.6: Comparing the RMS of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target two.

Figure E.7: Comparing the RMS of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target three.

Figure E.8: Comparing the RMS of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target four.

Figure E.9: Comparing the RMS of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target five.

Appendix F

Mean Frequency Analysis on Test A

Figure F.1: Comparing the MNF of dynamic contraction (*blue*) and sustained contraction (*red*) in the RPL muscle during basic balance test (Test A) for target two.

Figure F.2: Comparing the MNF of dynamic contraction (*blue*) and sustained contraction (*red*) in the RPL muscle during basic balance test (Test A) for target three.

Figure F.3: Comparing the MNF of dynamic contraction (*blue*) and sustained contraction (*red*) in the RPL muscle during basic balance test (Test A) for target four.

Figure F.4: Comparing the MNF of dynamic contraction (*blue*) and sustained contraction (*red*) in the RPL muscle during basic balance test (Test A) for target five.

Figure F.5: Comparing the MNF of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target one.

Figure F.6: Comparing the MNF of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target two.

Figure F.7: Comparing the MNF of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target three.

Figure F.8: Comparing the MNF of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target four.

Figure F.9: Comparing the MNF of dynamic contraction (*blue*) and sustained contraction (*red*) in the RS muscle during basic balance test (Test A) for target five.

Appendix G

Performance & %DET Analysis on Test B

Performance Agility Test

Performance was measured for Test B, based on a leveling up system. When the subject clears the screen of targets, the subject is then be promoted to the next stage. As the subject moves through the stages, the difficulty gradually increases until the allotted time is up. It can be seen from Table G.1 that the number of levels completed steadily increased as the subject progressed through the experiment.

Test B: Agility Test

Throughout the analysis of Test B, the first two seconds of the initial and final contractions were segmented and applied to the RQA program. There may not be enough sample sets to reach a viable trend due to the elimination of data for days 1 and 3. If one was to consider what was presented in Figure G.1, it can be seen that there was a development of higher levels of %DET for the RPL muscle with respect to the RS during the last three sessions. However the consideration of the first two seconds of the final contraction did not reveal any significant trends.

Table G.1: Game Score for Test B: Agility Test

Days	Day 1	Day 3	Day 6	Day 10	Day 13	Day 14	Day 16
Level	13	13	13	14	14	14	15

Figure G.1: Comparing the %DET of RS (blue) and RPL (red) muscles during basic balance test (Test A) for the first target .

Figure G.2: Comparing the %DET of RS (blue) and RPL (red) muscles during basic balance test (Test A) for the second target .

Appendix H

Root Mean Square Analysis on Test B

Figure H.1: Comparing the RMS of the RS (*blue*) and RPL (*red*) muscles during the first two seconds of the agility (Test B)

Figure H.2: Comparing the RMS of the RS (*blue*) and RPL (*red*) muscles during the last two seconds of the agility (Test B)

Appendix I

Root Mean Square Analysis on Test B

Figure I.1: Comparing the MNF of the RS (*blue*) and RPL (*red*) muscles during the first two seconds of the agility (Test B)

Figure I.2: Comparing the MNF of the RS (*blue*) and RPL (*red*) muscles during the last two seconds of the agility (Test B)

Appendix J

Root Mean Square Analysis on Soccer Training

Figure J.1: The first two seconds of the RMS analysis for Soccer Game 1 (blue), Game 5 (green) and Game 10 (red) measured from the RPL

Figure J.2: The last two seconds of the RMS analysis for Soccer Game 1 (blue), Game 5 (green) and Game 10 (red) measured from the RPL.

Figure J.3: The first two seconds of the RMS analysis for Soccer Game 1 (blue), Game 5 (green) and Game 10 (red) measured from the RS

Figure J.4: The last two seconds of the RMS analysis for Soccer Game 1 (*blue*), Game 5 (*green*) and Game 10 (*red*) measured from the RS

Appendix K

Mean Frequency Analysis on Soccer Training

Figure K.1: The first two seconds of the MNF analysis for Soccer Game 1 (*blue*), Game 5 (*green*) and Game 10 (*red*) measured from the RPL

Figure K.2: The last two seconds of the MNF analysis for Soccer Game 1 (*blue*), Game 5 (*green*) and Game 10 (*red*) measured from the RPL.

Figure K.3: The first two seconds of the MNF analysis for Soccer Game 1 (*blue*), Game 5 (*green*) and Game 10 (*red*) measured from the RS

Figure K.4: The last two seconds of the MNF analysis for Soccer Game 1 (*blue*), Game 5 (*green*) and Game 10 (*red*) measured from the RS

Appendix L

Root Mean Square Time Course on Test D

Figure L.1: Comparing the RS muscle RMS time course between Day 14 (blue) and Day 18 (green) during the single leg balance test (Test D)

Figure L.2: Comparing the RPL muscle RMS time course between Day 14 (blue) and Day 18 (green) during the single leg balance test (Test D).

Figure L.3: Comparing the RPL (blue) and RS (green) muscle with respect to RMS time course during Day 14 of the single leg balance test (Test D).

Figure L.4: Comparing the RPL (blue) and RS (green) muscle with respect to RMS time course during Day 15 of the single leg balance test (Test D).

Figure L.5: Comparing the RPL (blue) and RS (green) muscle with respect to RMS time course during Day 16 of the single leg balance test (Test D).

Figure L.6: Comparing the RPL (blue) and RS (green) muscle with respect to RMS time course during Day 17 of the single leg balance test (Test D).

Figure L.7: Comparing the RPL (blue) and RS (green) muscle with respect to RMS time course during Day 18 of the single leg balance test (Test D).

Figure L.8: Comparing the RPL (blue) and RS (green) muscle with respect to RMS time course during Day 19 of the single leg balance test (Test D).

Appendix M

Mean Frequency Time Course on Test D

Figure M.1: Comparing the RS muscle MNF time course between Day 14 (blue) and Day 18 (green) during the single leg balance test (Test D)

Figure M.2: Comparing the RPL muscle MNF time course between Day 14 (*blue*) and Day 18 (*green*) during the single leg balance test (Test D).

Figure M.3: Comparing the RPL (*blue*) and RS (*green*) muscle with respect to MNF time course during Day 14 of the single leg balance test (Test D).

Figure M.4: Comparing the RPL (*blue*) and RS (*green*) muscle with respect to MNF time course during Day 15 of the single leg balance test (Test D).

Figure M.5: Comparing the RPL (*blue*) and RS (*green*) muscle with respect to MNF time course during Day 16 of the single leg balance test (Test D).

Figure M.6: Comparing the RPL (*blue*) and RS (*green*) muscle with respect to MNF time course during Day 17 of the single leg balance test (Test D).

Figure M.7: Comparing the RPL (*blue*) and RS (*green*) muscle with respect to MNF time course during Day 18 of the single leg balance test (Test D).

Figure M.8: Comparing the RPL (*blue*) and RS (*green*) muscle with respect to MNF time course during Day 19 of the single leg balance test (Test D).

Appendix N

Root Mean Square Time Course on the Spinal Cord Injury Patient

Figure N.1: Comparing the Pre-Training (*blue*) and Post Training (*green*) of the SCI patient's MVC for the right TA muscle with respect to RMS time course

Figure N.2: Comparing the Pre-Training (*blue*) and Post Training (*green*) of the SCI patient's MVC for the right TA muscle with respect to RMS time course

Figure N.3: Comparing right TA (*blue*) and left TA (*green*) muscles with respect to RMS time course before training.

Figure N.4: Comparing right TA (*blue*) and left TA (*green*) muscles with respect to RMS time course after training.

Appendix O

Mean Frequency Time Course on the Spinal Cord Injury Patient

Figure O.1: Comparing the Pre-Training (*blue*) and Post Training (*green*) of the SCI patient's MVC for the right TA muscle with respect to MNF time course

Figure O.2: Comparing the Pre-Training (*blue*) and Post Training (*green*) of the SCI patient's MVC for the right TA muscle with respect to MNF time course

Figure O.3: Comparing right TA (*blue*) and left TA (*green*) muscles with respect to MNF time course before training.

Figure O.4: Comparing right TA (*blue*) and left TA (*green*) muscles with respect to MNF time course after training.

Appendix P

%DET Time Course on the Spinal Cord Injury Patient

Figure P.1: Comparing right TA (*blue*) and left TA (*green*) muscles with respect to %DET time course before training

Figure P.2: Comparing right TA (*blue*) and left TA (*green*) muscles with respect to %DET time course after training

Appendix Q

Independent Component Analysis

One of most famous problem which helps explain ICA is the "cocktail party problem". In this cocktail party everyone is enjoying themselves and talking with one another. Now assume that the host wishes to listen in on each speaker in the room, so he/she places microphones around the room (Number of microphones > speakers). Unfortunately, when this host plays back these recordings all he/she gets are different speakers talking over each other. This problem is very much like the problem with the recording of sEMG.

In order to provide a solution to this problem ICA assume that the model of this situation is a linear equation [43, 44]:

$$x_i(t) = a_{i1}s_1(t) + a_{i2}s_2(t) + \dots + a_{iN}s_N(t) \quad (Q.1)$$

Where, $x(t)$ is the recorded signal, a are parameters that are dependent of the distance of the microphone from the speakers, and finally $s(t)$ is the speech signal of each speaker. This equation can be expressed into a matrix form:

$$\text{Speakers} = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_n(t) \end{bmatrix} \mathbf{A} = \begin{bmatrix} s_1(t) \\ s_2(t) \\ \vdots \\ s(t) \end{bmatrix} \quad (Q.2)$$

Q.2 can be further written as:

$$s = \mathbf{A}x \quad (Q.3)$$

As it can be seen from Q.2, x and s are vectors of all recorded signal and all the original sources and $\mathbf{A}$ is known as the mixing matrix. This mixing matrix is what ICA estimates.

Therefore, in order to determine the original sources is to invert $\mathbf{A}$ to obtain s :

$$s = \mathbf{A}^{-1}x \quad (Q.4)$$

Appendix R

Results from Independent Component Analysis

Figure R.1: The independent components from the second elbow flexion computed by FastICA. The corresponding %DET was calculated to be 48.25%

Figure R.2: The independent components from the third elbow flexion computed by FastICA. The corresponding %DET was calculated to be 24.32%.

Figure R.3: The independent components from the fourth elbow flexion computed by FastICA. The corresponding %DET was calculated to be 52.5%

Figure R.4: The independent components from the fifth elbow flexion computed by FastICA. The corresponding %DET was calculated to be 39.13%

Figure R.5: The independent components from the sixth elbow flexion computed by FastICA. The corresponding %DET was calculated to be 68.83%

Figure R.6: The independent components from the seventh elbow flexion computed by FastICA. The corresponding %DET was calculated to be 79.19%

Figure R.7: The independent components from the eighth elbow flexion computed by FastICA. The corresponding %DET was calculated to be 84.08%

Figure R.8: The independent components from the ninth elbow flexion computed by FastICA. The corresponding %DET was calculated to be 92.71%

Figure R.9: The independent components from the tenth elbow flexion computed by FastICA. The corresponding %DET was calculated to be 55.05%

Figure R.10: The independent components from the eleventh elbow flexion computed by FastICA. The corresponding %DET was calculated to be 13.39%

Appendix S

Calculated Data

Table S.1: Average distance between RPL and RS

Method	Day 14	Day 15	Day 16	Day 17	Day 18	Day 18F
RMS	0.0816	0.0312	0.0356	0.036	0.0138	0.0058
MNF	42.299	16.721	24.148	17.547	10.799	9.965
%DET	42.610	24.238	18.395	9.446	8.241	9.512

Table S.2: Mean & standard deviation (SD) of %DET time course

Day	RPL Mean	RPL SD	RS Mean	RS SD
Day 14	71.47	10.71	28.86	10.900
Day 15	61.53	11.85	37.65	9.012
Day 16	69.22	7.063	50.83	9.938
Day 17	68.39	7.34	59.94	9.086
Day 18	31.63	8.92	34.47	8.370
Day 18F	23.95	9.45	28.20	5.207

Appendix T

Measured Game Score Data

Table T.1: Stability score from single leg balance test (Test D) Day 2 to Day 13

Day	Day 2	Day 3	Day 4	Day 5	Day 12	Day 13
Stability (%)	68	70	72	63	71	74

Table T.2: Stability score from single leg balance test (Test D) Day 14 to Day 18F

Day	Day 14	Day 15	Day 16	Day 17	Day 18	Day 18F
Stability (%)	70	78	68	76	74	72

Table T.3: Game score on beginner difficulty setting Trial 1 to 7

Day/Trial	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6	Trial 7
Day 2	192	165	343	233	311	253	372
Day 3	244	265	251	417	390	435	364
Day 4	489	440	352	298	545	411	387
Day 5	500	325	425	555	555	500	405

Table T.4: Game score on beginner difficulty setting Trial 7 to 14

Day/Trial	Trial 8	Trial 9	Trial 10	Trial 11	Trial 12	Trial 13	Trial 14
Day 2	356	426	175	280	334	394	446
Day 3	283	555	403	411	393	351	427
Day 4	385	435	324	473	413	440	344
Day 5	370	445	441	460	419	435	555

Table T.5: Game score on advance difficulty setting Trial 1 to Trial 5

Day/Trial	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5
Day 6	279	304	357	287	459
Day 7	165	276	375	365	252
Day 8	367	351	561	423	487
Day 9	281	246	478	365	451
Day 10	302	655	422	388	460
Day 11	270	396	500	329	470
Day 12	416	418	289	275	465
Day 13	474	484	447	485	609
Day 14	401	431	600	460	519
Day 15	560	545	500	554	340
Day 16	425	522	447	607	394
Day 17	581	655	552	655	497
Day 18	431	520	535	655	609

Table T.6: Game score on advance difficulty setting Trial 6 to Trial 10

Day/Trial	Trial 6	Trial 7	Trial 8	Trial 9	Trial 10
Day 6	308	458	379	289	469
Day 7	324	391	529	354	360
Day 8	439	413	381	461	325
Day 9	331	557	537	395	443
Day 10	454	334	510	436	382
Day 11	549	497	379	501	373
Day 12	553	655	379	397	655
Day 13	516	655	422	551	490
Day 14	500	597	495	373	563
Day 15	505	560	552	555	550
Day 16	423	552	419	508	552
Day 17	545	655	655	555	600
Day 18	560	572	600	511	655

Table T.7: Time Response from basic balance test (Test A)

Day/Target	Target 1	Target 2	Target 3	Target 4	Target 5
Day 1	4.92	5.33	4.12	6.83	7.44
Day 2	4.95	4.52	5.70	9.10	0.00
Day 4	4.62	4.38	5.80	7.32	3.17
Day 6	6.15	3.92	4.06	4.02	6.10
Day 8	4.97	5.25	9.03	6.39	3.55
Day 9	5.15	5.30	4.97	7.56	4.72
Day 11	4.80	5.04	5.75	8.88	0.00
Day 12	3.00	3.00	5.05	6.10	6.89
Day 17	4.74	4.08	5.08	6.47	5.17
Day 18	4.47	4.67	6.70	8.75	0.00
Day 18F	3.50	4.04	3.90	6.90	0.00

Appendix U

Measured %DET Data

Table U.1: Calculated %DET values for single leg balance (Test D) for the RS muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 18F
Initial 2 sec	72.585	88.060	84.117	91.663	75.780	33.991	22.7032
Mid 2 sec	66.385	73.802	55.233	81.327	48.305	25.414	24.717
Last 2 sec	0.0000	74.768	22.624	86.098	71.588	38.182	39.326

Table U.2: Calculated %DET values for single leg balance (Test D) for the RPL muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 18F
Initial 2 sec	71.587	33.166	48.064	65.85	72.298	37.153	23.926
Mid 2 sec	55.467	17.970	41.379	39.416	42.748	26.166	28.826
Last 2 sec	0.0000	21.610	25.352	31.461	35.683	29.079	40.796

Table U.3: Calculated %DET values for basic balance test (Test A) for the RPL muscle

Day/Target	Day 8	Day 9	Day 11	Day 12	Day 17	Day 18	Day 18F
Target 1 Burst	65.576	40.954	85.609	00.000	61.463	47.163	57.6925
Target 1 Sustained	65.556	37.529	78.839	53.502	44.321	31.797	32.877
Target 2 Burst	74.449	89.420	75.158	00.000	57.232	51.833	41.026
Target 2 Sustained	66.667	06.000	69.249	53.880	43.522	27.035	29.801
Target 3 Burst	49.434	84.667	78.316	80.071	43.304	20.812	20.000
Target 3 Sustained	50.620	41.253	67.324	68.359	40.183	21.036	18.000
Target 4 Burst	51.674	60.187	79.453	52.536	45.220	31.045	17.830
Target 4 Sustained	45.128	19.846	44.706	54.965	44.148	20.533	17.051
Target 5 Burst	0.0000	69.697	52.997	97.348	29.545	11.574	18.765
Target 5 Sustained	32.694	53.052	25.652	23.280	33.524	30.041	24.324

Table U.4: Calculated %DET values for basic balance test (Test A) for the RS muscle

Day/Target	Day 8	Day 9	Day 11	Day 12	Day 17	Day 18	Day 18F
Target 1 Burst	81.982	92.665	65.957	00.000	67.386	15.315	18.182
Target 1 Sustained	77.673	85.121	72.969	75.504	48.464	48.927	27.120
Target 2 Burst	89.109	92.733	68.071	00.000	32.515	67.424	12.121
Target 2 Sustained	79.316	91.573	75.670	69.836	12.500	32.465	17.713
Target 3 Burst	90.021	93.475	79.072	75.408	78.594	34.358	38.053
Target 3 Sustained	86.535	80.879	80.460	70.190	68.917	08.889	19.282
Target 4 Burst	94.430	80.053	43.795	71.403	69.833	38.157	32.930
Target 4 Sustained	87.858	87.137	11.848	79.159	48.526	19.043	21.500
Target 5 Burst	0.0000	88.732	67.188	46.252	30.723	19.774	21.094
Target 5 Sustained	80.173	90.232	55.263	33.333	00.000	10.000	34.865

Table U.5: Calculated %DET values for Agility (Test B) for the RPL muscle

Day/Time	Day 1	Day 3	Day 6	Day 10	Day 13	Day 14	Day 16
Initial 2 sec	94.059	17.510	28.839	88.914	80.165	75.323	65.767
Last 2 sec	87.779	88.997	47.654	91.776	72.511	67.104	84.870

Table U.6: Calculated %DET values for Agility (Test B) for the RS muscle

Day/Time	Day 1	Day 3	Day 6	Day 10	Day 13	Day 14	Day 16
Initial 2 sec	90.618	12.252	37.143	92.063	59.649	65.545	18.966
Last 2 sec	87.716	42.573	52.568	91.799	73.139	15.868	55.963

Table U.7: Calculated %DET values for soccer training for the RPL muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18
Game 1: Initial 2 sec	63.008	60.417	30.632	35.998	42.233	26.761
Game 1: Last 2 sec	73.745	64.329	55.968	61.010	85.652	63.2182
Game 5: Initial 2 sec	72.932	62.361	29.408	24.847	69.147	52.519
Game 5: Last 2 sec	65.192	33.059	61.613	68.716	73.782	62.919
Game 10: Initial 2 sec	43.022	45.051	46.376	59.888	19.444	22.838
Game 10: Last 2 sec	64.863	55.402	69.513	70.797	77.934	39.118

Appendix V

Measured Root Mean Square Data

Table V.1: Calculated RMS values for single leg balance (Test D) for the RPL muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 18F
Initial 2 sec	0.0657	0.0553	0.0527	0.0911	0.1451	0.0447	0.0452
Mid 2 sec	0.0775	0.0436	0.0317	0.0425	0.0790	0.0382	0.0414
Last 2 sec	0.0000	0.0351	0.0405	0.0531	0.0469	0.0345	0.0376

Table V.2: Calculated RMS values for single leg balance (Test D) for the RS muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 18F
Initial 2 sec	0.1307	0.3576	0.2148	0.2206	0.1468	0.0549	0.04902
Mid 2 sec	0.1692	0.1663	0.0790	0.1661	0.1200	0.0578	0.0395
Last 2 sec	0.0000	0.1079	0.0995	0.1200	0.0903	0.0468	0.0445

Table V.3: Calculated RMS values for basic balance test (Test A) for the RPL muscle

Day/Time	Day 8	Day 9	Day 11	Day 12	Day 17	Day 18	Day 18F
Target 1 Burst	0.0620	0.0541	0.0488	0.0000	0.0589	0.0395	0.0255
Target 1 Sustained	0.0650	0.0503	0.0596	0.0491	0.0483	0.0412	0.0250
Target 2 Burst	0.1158	0.2055	0.0478	0.0000	0.0675	0.0468	0.0221
Target 2 Sustained	0.0625	0.6860	0.0477	0.0599	0.0487	0.0304	0.0280
Target 3 Burst	0.0535	0.1089	0.1184	0.0870	0.0759	0.0302	0.0278
Target 3 Sustained	0.0734	0.0654	0.0574	0.0790	0.0622	0.0275	0.0259
Target 4 Burst	0.0000	0.0807	0.0585	0.0600	0.0658	0.0259	0.0250
Target 4 Sustained	0.0637	0.0508	0.0435	0.0623	0.0464	0.0344	0.0265
Target 5 Burst	0.0000	0.0601	0.0479	0.0748	0.0599	0.0000	0.0245
Target 5 Sustained	0.0630	0.0799	0.0444	0.0000	0.0493	0.0000	0.0282

Table V.4: Calculated RMS values for basic balance test (Test A) for the RS muscle

Day/Time	Day 8	Day 9	Day 11	Day 12	Day 17	Day 18	Day 18F
Target 1 Burst	0.0634	0.0816	0.0280	0.0000	0.0420	0.0218	0.0182
Target 1 Sustained	0.0413	0.0725	0.0317	0.0404	0.0291	0.0270	0.0185
Target 2 Burst	0.0930	0.4997	0.0529	0.0000	0.0374	0.0224	0.0231
Target 2 Sustained	0.0636	0.1210	0.0283	0.0425	0.0389	0.0227	0.0251
Target 3 Burst	0.1059	0.3080	0.0515	0.0513	0.0498	0.0297	0.0226
Target 3 Sustained	0.0990	0.0779	0.0375	0.0436	0.0383	0.0221	0.0207
Target 4 Burst	0.0853	0.2667	0.0436	0.0431	0.0485	0.0231	0.0209
Target 4 Sustained	0.0688	0.0929	0.0330	0.0467	0.0294	0.0301	0.0231
Target 5 Burst	0.0000	0.2153	0.0407	0.0466	0.0460	0.0173	0.0231
Target 5 Sustained	0.0489	0.1390	0.0370	0.0271	0.0307	0.0264	0.0198

Table V.5: Calculated RMS values for Agility (Test B) for the RPL muscle

Day/Time	Day 1	Day 3	Day 6	Day 10	Day 13	Day 14	Day 16
Initial 2 sec	0.1497	0.0564	0.0401	0.1874	0.0870	0.0624	0.1182
Last 2 sec	0.1354	0.1075	0.0891	0.2478	0.1456	0.1182	0.1469

Table V.6: Calculated RMS values for Agility (Test B) for the RS muscle

Day/Time	Day 1	Day 3	Day 6	Day 10	Day 13	Day 14	Day 16
Initial 2 sec	0.1198	0.0327	0.0245	0.1221	0.0346	0.0212	0.0236
Last 2 sec	0.1549	0.0378	0.1136	0.0346	0.0793	0.0349	0.0560

Table V.7: Calculated RMS values for soccer training for the RPL muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18
Game 1: Initial 2 sec	0.1182	0.0394	0.0554	0.0360	0.0370	0.0332
Game 1: Last 2 sec	0.5014	0.3394	0.1497	0.2107	0.0876	0.0742
Game 5: Initial 2 sec	0.1296	0.1274	0.0886	0.1708	0.0606	0.0366
Game 5: Last 2 sec	0.5014	0.3394	0.1497	0.2107	0.0876	0.0742
Game 10: Initial 2 sec	0.0392	0.0386	0.1303	0.1250	0.0711	0.0264
Game 10: Last 2 sec	0.2365	0.0795	0.2303	0.2415	0.1091	0.0310

Table V.8: Calculated RMS values for soccer training for the RS muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18
Game 1: Initial 2 sec	0.0454	0.0229	0.0253	0.0468	0.0204	0.0225
Game 1: Last 2 sec	0.0551	0.0323	0.0306	0.1614	0.0902	0.0480
Game 5: Initial 2 sec	0.0606	0.0265	0.0230	0.0424	0.0206	0.0359
Game 5: Last 2 sec	0.0544	0.0306	0.0353	0.0505	0.0553	0.0372
Game 10: Initial 2 sec	0.0453	0.0236	0.0293	0.0478	0.4680	0.0252
Game 10: Last 2 sec	0.0583	0.0335	0.0365	0.0686	0.1014	0.0264

Appendix W

Measured Mean Frequency Data

Table W.1: Calculated MNF values for single leg balance (Test D) for the RPL muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 18F
Initial 2 sec	60.269	52.502	57.895	52.618	61.534	86.532	86.739
Mid 2 sec	61.162	59.709	71.453	64.288	58.592	90.505	93.631
Last 2 sec	00.000	68.321	83.841	68.231	70.809	94.040	88.902

Table W.2: Calculated MNF values for single leg balance (Test D) for the RS muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 18F
Initial 2 sec	74.099	78.617	73.327	73.178	61.175	80.134	86.858
Mid 2 sec	72.042	89.027	81.993	82.496	67.346	86.148	86.148
Last 2 sec	0.0000	93.438	94.756	81.473	81.460	85.793	83.282

Table W.3: Calculated MNF values for basic balance test (Test A) for the RPL muscle

Day/Target	Day 8	Day 9	Day 11	Day 12	Day 17	Day 18	Day 18F
Target 1 Burst	75.475	72.145	56.739	0.0000	67.578	77.606	96.263
Target 1 Sustained	82.628	73.907	61.419	77.969	73.767	81.042	95.064
Target 2 Burst	70.407	48.646	69.103	0.0000	69.598	73.489	97.126
Target 2 Sustained	71.128	76.014	67.159	68.432	77.355	91.767	91.916
Target 3 Burst	85.536	62.617	54.436	54.604	67.356	93.523	91.727
Target 3 Sustained	75.355	74.798	61.521	69.992	74.776	89.613	102.118
Target 4 Burst	00.000	67.240	67.804	75.648	77.699	96.017	95.558
Target 4 Sustained	72.623	83.206	81.130	80.927	88.464	93.130	97.892
Target 5 Burst	00.000	75.834	71.228	61.955	87.189	0.0000	94.937
Target 5 Sustained	77.565	73.305	74.836	0.0000	90.225	0.0000	92.823

Table W.4: Calculated MNF values for basic balance test (Test A) for the RS muscle

Day/Target	Day 8	Day 9	Day 11	Day 12	Day 17	Day 18	Day 18F
Target 1 Burst	56.827	51.269	68.423	0.0000	76.104	87.971	97.553
Target 1 Sustained	55.366	49.577	64.783	69.307	82.987	89.386	91.609
Target 2 Burst	52.383	42.385	62.686	0.0000	91.888	78.702	80.767
Target 2 Sustained	51.730	55.890	67.622	65.129	69.005	88.753	96.125
Target 3 Burst	48.963	42.933	63.838	66.592	75.889	88.660	93.537
Target 3 Sustained	47.947	54.852	64.366	73.602	75.823	88.525	95.036
Target 4 Burst	44.567	45.240	68.005	70.833	83.170	88.575	93.302
Target 4 Sustained	50.895	48.010	79.033	71.779	81.418	96.126	94.120
Target 5 Burst	00.000	52.306	65.228	76.064	84.492	95.258	93.704
Target 5 Sustained	58.023	50.225	67.993	84.552	87.457	84.270	94.421

Table W.5: Calculated MNF values for Agility (Test B) for the RPL muscle

Day/Time	Day 1	Day 3	Day 6	Day 10	Day 13	Day 14	Day 16
Initial 2 sec	44.721	78.032	89.839	45.793	66.451	66.148	65.636
Last 2 sec	53.686	62.507	72.608	46.823	63.641	71.216	57.965

Table W.6: Calculated MNF values for Agility (Test B) for the RPL muscle

Day/Time	Day 1	Day 3	Day 6	Day 10	Day 13	Day 14	Day 16
Initial 2 sec	58.413	94.468	90.724	41.564	73.948	93.923	93.644
Last 2 sec	46.999	81.203	80.349	53.187	61.135	90.625	83.353

Table W.7: Calculated MNF values for soccer training for the RPL muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18
Game 1: Initial 2 sec	65.399	74.192	57.385	78.820	92.949	89.513
Game 1: Last 2 sec	45.061	36.041	49.440	49.691	64.373	69.061
Game 5: Initial 2 sec	61.799	60.828	65.098	59.044	68.479	88.381
Game 5: Last 2 sec	47.763	65.320	38.802	50.804	69.063	77.299
Game 10: Initial 2 sec	85.202	74.344	62.970	61.216	76.845	86.860
Game 10: Last 2 sec	56.552	64.939	57.743	48.479	60.275	69.063

Table W.8: Calculated MNF values for soccer training for the RS muscle

Day/Time	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18
Game 1: Initial 2 sec	75.136	100.79	90.797	93.093	92.350	84.122
Game 1: Last 2 sec	60.307	70.071	68.963	76.191	56.052	72.244
Game 5: Initial 2 sec	58.079	91.862	92.737	75.811	88.831	75.270
Game 5: Last 2 sec	64.512	87.757	67.994	66.079	61.851	78.414
Game 10: Initial 2 sec	83.664	89.819	94.267	68.165	82.492	91.296
Game 10: Last 2 sec	72.824	75.555	70.229	61.824	54.101	76.951

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