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Fractal Based Complexity Measure and Variation in Force During Sustained Isometric Muscle Contraction: Effect of Aging

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Abstract— **This study has investigated the effect of age on the fractal based complexity measure of muscle activity and variance in the force of isometric muscle contraction. Surface electromyogram (sEMG) and force of muscle contraction were recorded from 40 healthy subjects categorized into: Group 1: Young - age range 20-30; 10 Males and 10 Females, Group 2: Old - age range 55-70; 10 Males and 10 Females during isometric exercise at Maximum Voluntary contraction (MVC). The results show that there is a reduction in the complexity of surface electromyogram (sEMG) associated with aging. The results demonstrate that there is an increase in the coefficient of variance (CoV) of the force of muscle contraction and a decrease in complexity of sEMG for the Old age group when compared with the Young age group.**

I. INTRODUCTION

There are reported studies that as we age, our bodies undergo substantial changes. Lipsitz and Goldberger [1] proposed that there is a reduction in the complexity of a physiological or behavioral control system with age and disease. They postulated that the reduced complexity reflects the underlying structural (component) and functional (coupling) changes in the organization of the system. A loss in system complexity is reflected by the loss or impairment of functional components and/or due to altered nonlinear coupling between the components. There is a reduction in the complexities in the brain, skin and the eye [2], [3], the cardiac cycle, and our gait pattern [4], [5], [6]. While the loss of complexity has been studied for the skin and neural cells and the retinal vessels, no study has reported the change in the complexity of the neuromuscular system with aging.

Aging is considered to have a strong impact on the parameters of muscle functions such as strength, endurance, and fatigue. While earlier studies have established that aging is associated with significant decline in muscle strength [15], [16], especially after the age of 60, the relationship is not simple, and not universally accepted. Miller [17] and Boncompagni et al [18] have observed that this reduction in muscle strength is not always the case. Petrofsky and Lind [9] observed an increase in isometric endurance till the 5th decade in aging.

Changes in the neuromuscular system based on the effects of age can be demonstrated by measuring the loss of muscle mass and muscular strength in older adults [7], [8] There is associated decrease in muscle mass, caused by loss of muscle fibers numbers and decrease in muscle fiber sizes [20], leading to diminished muscle function.

Research studies has reported that there is a net increase in the motor unit density [20] and reduction in number of motor units [18] due to age. This could lead to a reduction in the complexity of the muscle activity, leading to reduction in the complexity of the electromyogram. Based on the above, this study has investigated the impact of aging in the muscle complexity using complexity measure, fractal dimension of sEMG.

This research has experimentally investigated the age related change in Fractal Dimension (FD), a measure of complexity, of surface electromyogram and the change in force variability during isometric contraction of the *biceps*. The study has also examined the correlation between the two factors - FD and variability of the force of contraction on aging.

II. METHODS

A. Subjects

40 healthy volunteers from Australian urban (multi-racial) population, with no symptoms or history of major neurological or movement disorder participated in this study. The participants were categorized into: Group 1: Young - age range 20-30; 10 Males and 10 Females, Group 2: Old - age range 55-70; 10 Males and 10 Females. All the participants were moderately active and performed non-strenuous exercises 3-5 times/ week. None of the participants participated in any competitive level sports or regular rigorous exercises.

Prior to the start of the experiment, the purpose of the study, procedures and risks associated with participation were explained and written informed consent was obtained from each subject. The experiments were approved by RMIT University Human Research Ethics Committee and were conducted in accordance with Declaration of Helsinki of 1975, as revised in 2004.

B. Surface Electromyogram Recording Procedures

SEMG signals were recorded using a proprietary Delsys (Boston, MA, USA) sEMG acquisition system. The system supports bipolar recording and has a fixed gain of 1000, CMRR of 92 dB and bandwidth of 20-450 Hz, with 12dB/ octave roll-off. The sampling rate is fixed at 1000 samples/second, and the resolution is 16 bits/sample. Bipolar electrodes manufactured by Delsys (Boston, MA, USA) were placed on the anterior upper arm above the biceps and in line between the anticubital fossa (depression in the front of the elbow - lateral to the biceps brachii tendon) and the acromion

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process (part of the scapula which extends over the shoulder), at 1/3rd distance from the anticubital fossa. Prior to electrode placement, the skin area was cleaned with alcohol swabs and lightly exfoliated with paper towel to reduce skin impedance and ensure good adhesion of the electrodes.

C. Experimental Protocol

During the experiments, the volunteers were seated on a sturdy and adjustable chair with their feet flat on the floor and their upper arm was rested on the surface of an adjustable desk such that the forearm was vertical (refer Fig.1). The elbow was maintained at 90 degrees, with the fingers in line with a wall mounted force sensor (S-type force sensor - INTERFACE SM25) attached to a comfortable hand sized ring with a flexible steel wire, and the ring was held on the wrist of the participant.

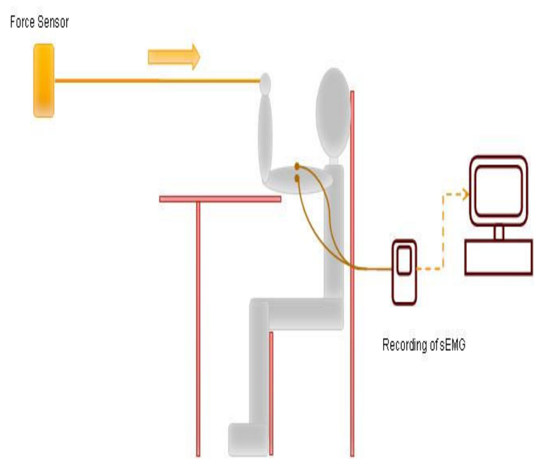

Fig. 1. Illustration of the experiment protocol.

To determine the Maximal Voluntary Contraction (MVC), three maximal contractions of 5 seconds were performed with 120 seconds rest time between each effort. The participants pulled the ring and the force of contraction was recorded. The average of these readings was considered to be the MVC. If there were any outliers, the experiment was repeated. After identifying MVC, the participants performed isometric contractions at MVC until when the level of force was dropped by 10%. The duration of each contraction was referred to as the endurance period (T_E). This was found to be different for different participants.

D. Data Analysis

Data analysis was performed off-line using the MATLAB 2009a software environment (The MathWorks Inc., Natick, Massachusetts, USA). All the recordings were segmented into 1 sec segments for the analysis. The initial 3 secs of the recordings of sEMG and force were removed prior to the data analysis to avoid the initial force stabilization.

In order to compare the results across all subjects, the time axis was normalized such that the full length corresponded to the endurance period (T_E) and this was divided into 5 equal segments, Start $(T_0), 0.25T_E, 0.5T_E, 0.75T_E$ and T_E. The start of the exercise was labeled as T_0 and the end of the exercise was labeled as T_E (the endurance limit). Fractal dimension was computed for each segments as explained below:

1) Computation of Fractal Dimension (FD): Fractal dimension (FD) is the measure of the complexity of a signal. FD of sEMG was computed using Higuchi algorithm [12] to estimate the complexity of the underlying neuromuscular system. This algorithm yields a more accurate estimation of fractal dimension [11] for physiological signals. The procedure is explained in [13], [14]. This has been represented in Fig.2, where FD is the slope of the linearly decreasing length of the curve, L over the scale k.

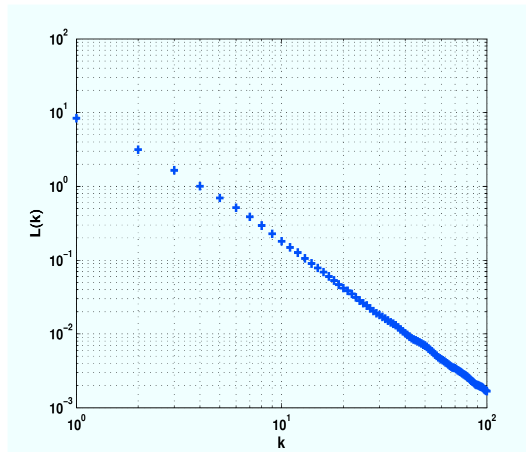

Fig. 2. FD - Slope of the linearly decreasing length of curve L over the scale k.

2) Coefficient of Variation: The time series recording from the force sensor was analysed to obtain the variability in the force using the Coefficient of Variation (CoV). This is obtained by normalizing the standard deviation (σ) by the mean (μ) force.

$$CoV = \sigma/\mu \quad (1)$$

3) Correlation: The CoV and FD of each of the segments were computed and placed in two arrays, the location corresponding to the age label. Each data was labeled based on the age starting from 20 years and ending at 30 years for the Young age group and for the Old age group the label was started from the age of 55 years and ended at 70 years. Correlation between the array of CoV of force at MVC and the array of FD (complexity) was computed using the correlation coefficient.

III. RESULTS

Fig. 3 is the plot of the Coefficient of Variance (CoV) (Mean and SD) during isometric contraction at MVC for young and old cohorts. The results show that CoV increased for older cohort when compared with the younger cohort at MVC of muscle contraction. This denotes that there is a large variation in the control for the old age group. This is confirmed in Fig. 4 where there is a quadratic increase in the CoV between the two age groups.

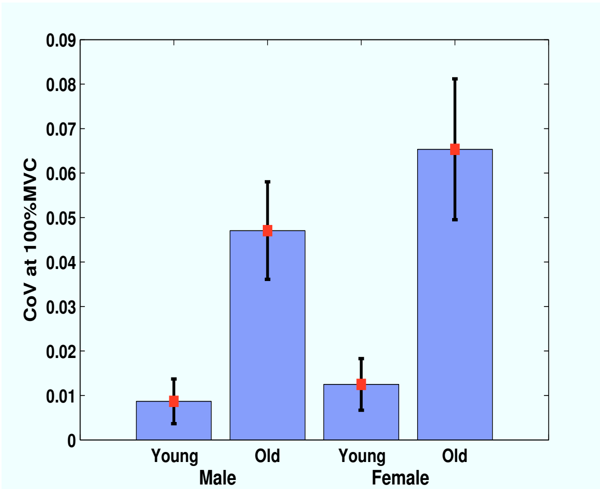

Fig. 3. Mean and SD plot of CoV at MVC.

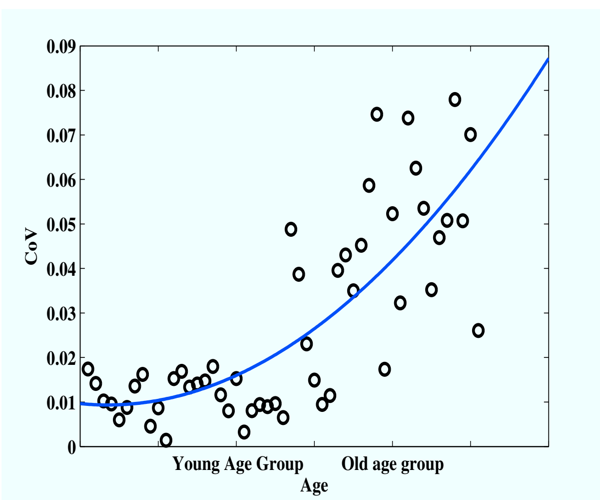

Fig. 4. CoV (Quadratic function) increasing for the Old age group when compared with the Young age group.

Fig. 5 is the plot of the mean Fractal Dimension (FD) of sEMG for the two age groups for 100% MVC. From this figure, it is observed that there was a significant reduction in the FD with age at 100% MVC. The correlation between the CoV and FD for 100% MVC (r^2 = 0.82) between the CoV and FD shows that there is an inverse relationship between the Cov of force and complexity for the two age groups (Fig. 6).

IV. DISCUSSION

This study has experimentally established that there is age associated increase in the force variability, measured by Cefficient of Variation (CoV). This study has established the association of ageing with the reduction in the fractal dimension of surface electromyogram. Fractal Dimension (FD) measures the complexity of a signal or a system. The results show that the FD reduces for older age group (55 - 70 years) than the younger age group (20 -30 years). The results indicate that there is a correlation between the age associated reduction in the complexity and increase in the variability of muscle force. This association can be attributed to the reduction in the number of motor units [23] and associated increase in the motor unit density [20]. The results demonstrate that the age associated reduction in complexity of sEMG is closely related with the increase in CoV of the force of muscle contraction. One of the explanations linked to reduction in FD is the 'reduction in diversity' [10].

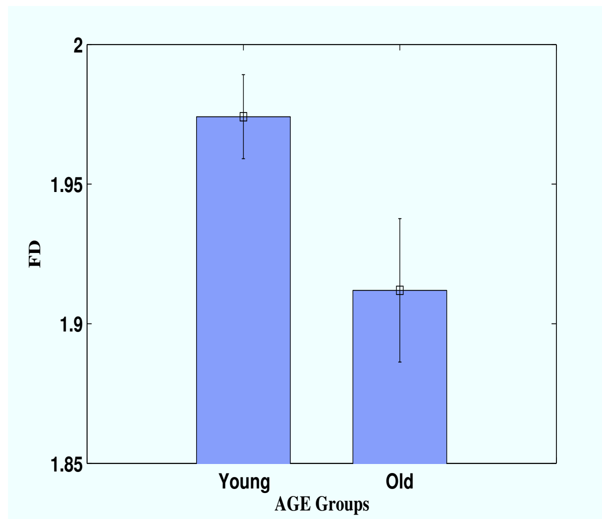

Fig. 5. Complexity Measure (FD) for the Young and Old age groups.

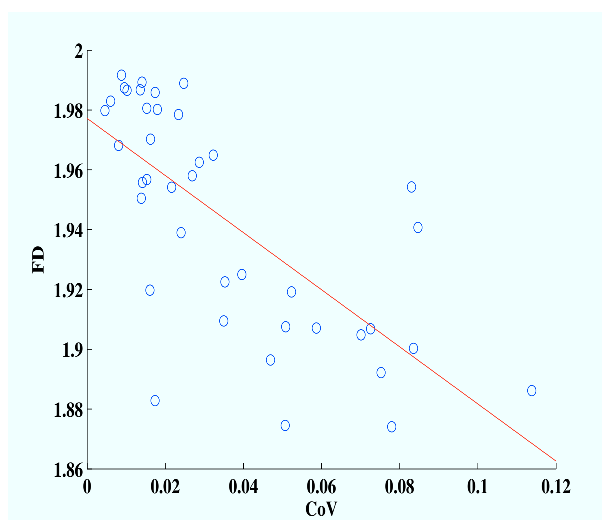

Fig. 6. FD vs CoV between age two groups (fitted with linear function).

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