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EFFECTS OF AGING AND EXERCISE ON DYNAMIC POSTURAL CONTROL: ANALYSIS OF MUSCLE SYNERGIES

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Program of Sport Sciences and Technology
MASTER OF SCIENCE THESIS

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APPROVAL PAGE

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YAYIMLAMA VE FİKRİ MÜLKİYET HAKLARI BEYANI

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ETHICAL DECLARATION

In this thesis study, I declare that all the information and documents have been obtained in the base of the academic rules and all audio-visual and written information and results have been presented according to the rules of scientific ethics. I did not do any distortion in data set. In case of using other works, related studies have been fully cited in accordance with the scientific standards. I also declare that my thesis study is original except cited references. It was produced by myself in consultation with supervisor Assoc. Prof. Dr. Pınar ARPINAR AVŞAR and written according to the rules of thesis writing of Hacettepe University Institute of Health Sciences.

Esranur YILDIRAN CARLAK

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[1] eş: a Turkish word refers to husband or wife without any sex emphasis; also means equal, even.

ABSTRACT

Yıldıran Carlak, E., Effects of Aging and Exercise on Dynamic Postural Control: Analysis of Muscle Synergies, Hacettepe University Graduate School of Health Sciences, M.Sc. Thesis in Sports Sciences and Technology, Ankara, 2023. This study aims to investigate human motor control mechanisms providing coordination of voluntary dynamic movements under the effects of “natural aging” and "participation in regular exercise". Electrophysiological activities of selected lower extremity muscles and ground reaction forces are recorded simultaneously by surface electromyography and force platform, respectively during “voluntary body sway” (VBS). The healthy older physically active group (master athletes) and the healthy sedentary groups (young and older) are included to the study. Principal Component Analysis is used to determine the number of muscle modes and the composition of muscle modes i.e., reciprocal or co-activation contraction patterns. Synergy index is calculated with the Uncontrolled Manifold (UCM) Hypothesis. The results of the UCM analysis for the dominant side are for the first time compared with the non-dominant side. The main findings of the study: there was no age or exercise effect *i)* on the number of muscle modes (the same for all groups) and *ii)* on contraction pattern (reciprocal pattern for all groups), *iii)* the young sedentary group had lower values for UCM variance components than the older groups, probably depending on experiencing the lowest task difficulty, *iv)* synergy index was highest for older sedentary group, and lowest for master athletes, *v)* older sedentary group showed less flexible, more rigid motor control strategies, *vi)* UCM variance components and synergy index values were different in the multi-muscle coordination of dominant and non-dominant lower extremity. Re-examining the VBS movement by dividing it into phases was recommended to reach more detailed information about muscle synergy patterns. It was revealed that the differences in multi-muscle coordination between dominant and non-dominant limbs should not be neglected.

Keywords: Hierarchical Control of Movement, Muscle Synergies, Master Athletes, Aging Motor Control, Uncontrolled Manifold Hypothesis.

ÖZET

Yıldıran Carlak, E., Dinamik Postür Kontrolü Üzerine Yaş ve Egzersizin Etkisi: Kas Sinerjileri Analizi, Hacettepe Üniversitesi Sağlık Bilimleri Enstitüsü Spor Bilimleri ve Teknolojisi Programı Yüksek Lisans Tezi, Ankara, 2023. Bu çalışmanın amacı, insan vücudunun gerçekleştirdiği istemli dinamik hareketlerin koordinasyonunu sağlayan motor kontrol mekanizmaları üzerine “doğal yaş alma” ve “düzenli egzersize katılım” etkilerinin incelemesidir. Çalışmaya düzenli egzersiz yapan yaş almış sağlıklı yetişkin grup (master atletler) ve sağlıklı sedanter yetişkin (genç ve yaş almış) gruplar dahil edilmiştir. Seçilen alt ekstremite kaslarının elektrofizyolojik aktiviteleri ve yer tepki kuvvetleri “istemli vücut salınımı” (İVS) hareketi sırasında yüzeyel elektromiyografi ve kuvvet platformu tarafından eş zamanlı olarak kaydedilmiştir. Kas modu sayısının ve kas modlarının kasılma modellerinin (resiprokal veya koaktivasyon) belirlenmesinde Temel Bileşenler Analizi kullanılmıştır. Sinerji indeksi Kontrol Edilmeyen Manifold (İng., *Uncontrolled Manifold, UCM)* Hipotezine göre hesaplanmıştır. UCM analizinin sonuçları ilk defa dominant ve dominant olmayan alt ekstremiteler arasında karşılaştırılmıştır. Araştırmanın temel bulguları: *i)* kas modu sayısı (tüm gruplar için aynı) ve *ii)* kasılma modeli (tüm gruplar için resiprokal model) üzerinde yaş veya egzersiz etkisi görülmemiştir, *iii)* genç sedanter grup UCM varyans bileşenleri için yaş almış gruplardan anlamlı ölçüde daha düşük değerler göstermiştir, *iv)* sinerji indeksi yaş almış sedanter grupta en yüksek, master atletlerde en düşük bulundu, *v)* yaş almış sedanter grup daha az esnek, daha rijit motor kontrol stratejileri sergilemiştir, *vi)* UCM varyans bileşenleri ve sinerji indeksi değerleri, dominant ve dominant olmayan alt ekstremitenin çoklu kas koordinasyonunda farklılık göstermiştir. İVS hareketinin fazlara ayrılarak incelenmesi kas sinerjileri hakkında daha detaylı bilgiye ulaşılmasına katkıda bulunacaktır. Dominant ve dominant olmayan alt ekstremitelerin çoklu kas koordinasyonundaki farklılıkların ihmal edilmemesi gerektiği ortaya koyulmuştur.

Anahtar Kelimeler: Hareketin Hiyerarşik Kontrolü, Kas Sinerjileri, Master Atletler, Motor Kontrol ve Yaşlanma, Kontrol Edilmeyen Manifold Hipotezi

TABLE OF CONTENTS

8. **APPENDIX**

SYMBOLS AND ABBREVIATIONS

A	Anterior peak of the sway cycle
A/D	Analog-to-digital
AP	Anterior-posterior (direction)
BF	Biceps Femoris muscle
cm	Centimeter
CNS	Central nervous system
COM	Center of mass
COP	Center of pressure
D	Dorsal muscle group
$\mathbf{d_x}$	Displacement in the anteroposterior direction
$\mathbf{f_{ORT}}$	The orthogonal subspace to UCM subspace
$\mathbf{f_{UCM}}$	The UCM linear subspace
$\mathbf{F_x}$	Force in x-axis
$\mathbf{F_y}$	Force in y-axis
$\mathbf{F_z}$	Force in z-axis
GM	Gastrocnemius Medialis muscle
hr	Hour
Hz	Hertz
IPAQ	International Physical Activity Questionnaire
iEMG	Integrated EMG
$\mathbf{iEMG_{Norm}}$	Normalized integrated EMG

$iEMG_{Ref}$	Reference integrated EMG
$iEMG_{Rest}$	Integrated EMG at rest
$iEMG_{SC}$	Integrated EMG of sway cycle
İVS	İstemli vücut salınımı
K	Kilometer
k_i	Coefficients of the regression equation
kg	Kilogram
km	Kilometer
J	Jacobian Matrix
m	Meter
M-Mod	Muscle modes matrix
M_x	The moment of force around the x-axis
M_y	The moment of force around the y-axis
M_Y	Moment in mediolateral direction
M_z	The moment of force around the z-axis
min	Minute
N	Number of participants
NMLab	Neuromuscular Control Research Laboratory
P	Posterior peak of the sway cycle
PC	Principal component
PC1	First principal component
PC2	Second principal component
PC3	Third principal component

PC4	Forth principal component
PCA	Principal component analysis
RF	Rectus Femoris muscle
SD	Standard deviation
sEMG	Surface Electromyography
SENIAM	Surface Electromyography for the Non-Invasive Assessment of Muscles
SOL	Soleus muscle
ST	Semitendinosus muscle
SVD	Singular Value Decomposition
TA	Tibialis Anterior muscle
UCM	Uncontrolled Manifold
V	Ventral muscle group
VBS	Voluntary body sway
VL	Vastus Lateralis muscle
VM	Vastus Medialis muscle
$\mathbf{V_{ORT}}$	Variance orthogonal to the UCM
$\mathbf{V_{UCM}}$	Variance within the UCM
V-D	Ventral and dorsal muscle group together
ΔM-Mod	Derivative of muscle modes matrix
$\mathbf{\Delta M_Y}$	Derivative of moment in mediolateral direction
ΔV	Synergy index
#S	The subject number

LIST OF FIGURES

LIST OF TABLES

To my lovely precious family…

Sevgili anneme ve babama, Kaan’a, Cansu’ya, eşim Arda’ya…

1. INTRODUCTION

1.1 Definition of the Research Problem

Decrease in postural control ability due to advanced age negatively affects daily activities and increases risk of falling. Regular exercise positively affects postural control by improving balance skills and reducing age-related proprioceptive decline. When considering the worldwide growth rate of the population over the age of sixty and the fact that participation in physical activity gradually decreases with age, investigating the effects of regular exercise on the postural control of older individuals appears to be important.

It has been reported that the total muscle cross-sectional area decreases by approximately 10-20% between the ages of 20 and 50, and by approximately 40% between the ages of 20 and 80 in sedentary individuals (1). As a result of this loss of muscle mass and the decrease in the capacity of the muscles to exert force, known as *sarcopenia*; compensatory movements, decreased movement speed and loss of balance are observed in daily activities of older individuals. In the clinical examination of the effects of age-related changes in musculoskeletal system structures on motor functions, center of mass or center of pressure parameters (sway oscillation parameters) during quiet stance, sit-to-stand mechanics and muscle activities during these movements are frequently evaluated by electrophysiological and biomechanical analyzes. The muscle activation amplitudes and their temporal change data obtained by the surface electromyography (sEMG) method can be used to examine the role of multi-muscle coordination (neuromuscular control) in dynamic movements and maintaining posture. Understanding the effects of functional losses associated with natural aging on multi-muscle, intersegment coordination in dynamic movements will be instructive.

Studies have been investigating only the effect of aging or only the effect regular exercise on multi-muscle coordination; however, the effect of regular exercise on multi-muscle coordination between different age groups has not been compared. Although it is known that motor coordination efficiency decreases with the effect of aging, the current knowledge in the literature is insufficient to answer whether older people who exercise regularly have the high efficiency level observed in healthy young individuals. Therefore, as a result of the need to investigate the effects of regular exercise and aging, a research study was designed involving groups of participants of different ages (young and older) and different levels of physical activity (sedentary and regular exercisers).

1.2 Objectives and Scope of the Thesis Study

The objective of this thesis study is to examine the effects of “natural aging” and “participation in regular exercise” on the motor control mechanisms that control the voluntary dynamic movements of the lower extremity of human body. For this purpose, three groups of participants, consisting of male and female healthy sedentary and runner individuals between the ages of 20-69 living in Ankara, were included in the study which are healthy older physically active group who exercise regularly (competitor master athletes) and healthy sedentary groups (young and older).

The multi-muscle coordination strategies used by the participants while maintaining posture control during repetitive motion of voluntary body sway (VBS) were examined. Muscle activity magnitude-time changes of bilaterally selected muscles were determined electrophysiologically with the superficial electromyography method during the specified dynamic movement. Simultaneously with muscle activity data record, ground reaction forces were recorded to correlate with motor output. Experimental measurements and analyzes aimed to evaluate the effect of "participation in regular exercise" in the elderly by comparing two older groups who are regular exerciser and physically inactive i.e., sedentary. Moreover, interfering the effect of “natural aging” by comparing young and older physically inactive sedentary groups was aimed, as well.

The comparative examination of motor coordination elements of the aforementioned groups was based on "*Muscle Synergies Theory*" also called *Hierarchical Control of Movement Theory* (2, 3, 4) to quantitatively reveal some hypothetical variables that are claimed to reflect neuromuscular control characteristics of human body, such as “*muscle modes*” and “*synergy index*”. Principal Component Analysis (PCA) is used to determine muscle modes and reciprocal or co-activation strategies followed by muscle modes. The synergy index is determined with the Uncontrolled Manifold (UCM) Hypothesis. In addition, all analyzes for the dominant side were compared with the non-dominant side. The hypotheses and research questions tested within the scope of this study based on group comparisons to reveal:

i) the effects of age and regular exercise on *the number of muscle modes* reflecting arrangements at the lower level of the theoretical hierarchical control mechanism of the human movement system,

ii) the effects of age and regular exercise on *muscle mode composition*,

iii) the effects of age and regular exercise on *synergy index* reflecting arrangements at the higher level of the theoretical hierarchical control mechanism of the human movement system and motor coordination efficiency.

With this thesis, it was expected to answer the research questions and contribute to the literature at the theoretical level by examining the neuromuscular control of lower extremity coordination during a voluntary dynamic movement in terms of the effect of “natural aging” and “participation in regular exercise”. Moreover, it was also expected to obtain information on the role of “participation in regular exercise” in multi-muscle coordination of older individuals i.e., the possible positive effects of continuous and regular exercise in mitigating or even preventing the decline in postural control caused by natural aging.

1.3 Importance of the Thesis Study

Understanding the functional change in the neuromuscular system associated with natural aging is among the priority issues, in order to take measures to ensure the participation of the increasingly aging population in social life and to reduce health expenditures. In this perspective, providing information on the role of regular exercise in preventing age-related losses in multi-muscular coordination appears to be important. The theoretical information that was aimed to be reached has the potential to open the door to new project studies in which research would be carried out under the sub-headings of "exercise type, duration and intensity" in order to reach qualified information on the role of exercise in the prevention of factors such as postural control problems due to aging, loss of physical independence, risk of falling.

In the current literature there are studies suggesting that muscle synergies analysis can be a new “biomarker” that can be used for the early diagnosis of postural control disorders due to Parkinson's (5) and to determine the fall risks of older adults without a clinically determined neurological disease (6). It is thought that muscle synergies analysis has the potential to be proposed as a “new diagnostic method” in the future by including neurologic patient groups at different diagnostic levels and examining the differences during the progression of the disease.

This thesis study has significance in terms of the inclusion of participants from different ages and physical activity levels (older physically active adults, young and older physically inactive adults), the selection of exercise type (aerobic running) and the investigation of the effect of *lower limb laterality* on muscle synergies.

Investigation of the Effect of Age and Exercise

In this thesis study, hierarchical control elements of human motor control mechanism (number of muscle modes, muscle mode composition, synergy index) were compared on individuals of different ages and physical activity levels i.e., older physically active group, young and older physically inactive groups during a dynamic lower extremity movement. Therefore, by analyzing the effects of “age” and “participation in regular exercise” together for the first time, it was expected to contribute at the theoretical level to the discussions on the effects of the both factors on the neural control of motor coordination.

Choosing Aerobic Running Effort as a Type of Physical Activity Included in the Content of Regular Exercise

Aerobic running is an accessible and sustainable exercise which has become increasingly popular among master athletes in the recent years. In this study, the chronic effect of the aerobic running effort on motor control mechanisms in older individuals was examined comparatively among older physically active group and physically inactive groups (young and older) for the first time.

In this way, it was aimed to investigate the possible role of regular and long-term aerobic running effort in the protection and even improvement of neuromuscular control components, which change with natural aging. The findings of this thesis study have the potential to provide evidence on the effect of “regular aerobic running exercise” on motor coordination of older people as a candidate of a viable and sustainable solution to reduce the risks of falls, injuries, and loss of physical function by increasing quality of life and independence in daily life movements which are known to decrease due to aging and inactivity.

Investigation of the Effect of Lower Limb Laterality on Muscle Synergies

Considering the *lower limb laterality* approach, first defined by Peters (7), that the dominant and the non-dominant lower limbs differentiates in terms of their roles on motor control i.e., *motor execution* limb is the dominant one and *stability* limb is the non-dominant one, we thought that multi-muscle coordination that we investigate in this study could differ between the two sides of the lower limbs. Therefore, we wanted for the first time to compare dominant and non-dominant lower extremity multi-muscle coordination in terms of Muscle Synergies Analysis.

1.4 Hypotheses and Research Questions

The following hypotheses were tested within the scope of the thesis study and answers to the research questions sought.

Number of Muscle Modes (associated with the motor flexibility and the size of motor repertoire):

Hypothesis 1: The number of muscle modes may be higher in the young sedentary group than in the older sedentary group (8).

Hypothesis 2: The number of muscle modes may be higher in the master runners than in the older sedentary group (9).

Research Question 1: Is there a difference in the number of muscle modes between the young sedentary group and the master runners?

Composition of Muscle Mode (associated with the co-activation level):

Hypothesis 3: The older sedentary group may have higher co-activation level in muscle mode composition than in the younger sedentary group (10, 11, 12).

Hypothesis 4: The older sedentary group may have higher co-activation level in muscle mode composition than in the master runners (13, 14).

Research Question 2: Is muscle mode composition different for the young sedentary group and the master runners?

Synergy Index (associated with multi-muscular motor coordination efficiency):

Hypothesis 5: Synergy index may be higher in the young sedentary group than in the older sedentary group (15, 16, 17).

Hypothesis 6: Synergy index may be higher in the master runners than in the older sedentary group (14).

Research Question 3: Is synergy index different for the young sedentary group and the master runners?

Lower Limb Laterality on Muscle Synergies

Research Question 4: Does multi-muscle coordination characteristics of left-right (dominant vs. non-dominant) lower extremity during dynamic postural control of VBS motion of the three groups differentiate based on the *lower limb laterality* approach?

1.5 Limitations of the Thesis Study

The limitations of this study are listed below:

- Only runners were included in the trained group,
- All participants were selected from the population living in Ankara,
- Analyzes made only for the lower extremity (i.e., included muscles were ankle dorsi flexor and plantar flexor, and knee extensors and flexors, where any of trunk muscles were included),

- Data such as “exercise history”, “training age”, “training intensity scale” are not determined as an inclusion or exclusion criterion and are partially presented as a descriptive feature considering the current sample size in the trained group,
- The moment of force in x (anteroposterior) direction, M_Y was accepted as the performance parameter of UCM analysis (see section 3.4.1 *Determination of the Performance Parameter*). Therefore, it was assumed that the three participant groups of this study, i.e., master athletes, young sedentary group and older sedentary group, stabilizes the value or the time profile of the M_Y parameter as a motor output (see section 2.5 *Uncontrolled Manifold (UCM) Hypothesis*).

2. LITERATURE REVIEW

2.1 Postural Control

Postural control can be defined as the natural ability to keep the body's center of mass within the boundaries of the support surface (18) by providing temporal and spatial multi-muscle coordination (19) while the central nervous system (CNS) continuously collects and integrates somatosensory (visual, vestibular, tactile, proprioceptive) information from the peripheral nervous system (20). Postural control can be classified in two ways, static and dynamic. In static postural control, the movement of body members and body's center of mass is minimized (21). In dynamic postural control, predictable or unpredictable internal or external effects disturbing postural balance are balanced by motor coordination between muscles (22) and the body's center of mass moves in a controlled manner within the targeted limits (23).

It is known that physical characteristics related to the nervous and musculoskeletal systems (21, 24, 25), physiological processes such as response to environmental influences and fatigue (26, 27) and psychological factors such as anxiety, focus (28, 29) are among the factors affecting postural control in healthy individuals.

There are also evidences that physical and physiological changes depending on age (30, 31) and regular exercise (32, 33) or inactivity (34, 35) affects dynamic postural control.

2.1.1 Effects of Ageing on Postural Control

According to the World Population Ageing report of United Nations (2020) (36), the proportion of the worldwide population aged 65 years or over is expected to increase from 9.3% in 2020 to around 16.0% in 2050. In Turkey, according to the report released by Turkish Statistical Institute in 2020 (37), while the share of the population over the age of 65 was 9.5% in 2020, this share is predicted to reach 16.3% in yet 2040 and 22.6% in 2060.

With the effect of natural aging, changes are observed in the neuromuscular system that adversely affect postural control (38, 39). Postural control is adversely affected by the changes observed in the neuromuscular system due to the natural aging.

These changes in the neuromuscular system are mainly reported as:

i. sarcopenia that is known as a general decrease in motor performance and a decrease in muscle mass and a loss of function (40),
ii. a decrease in maximal muscle strength (41, 42),
iii. a decrease in sensitivity of strength control (43, 44),
iv. an increase in body center of pressure (COP) deviations during quite stance (4, 45, 46, 47),
v. a decrease in the voluntary movement capacity of the body center of mass (48, 49).

Sarcopenia in the Elderly

One of the most noticeable effects of aging is a decrease in muscle strength (42). The loss of muscle force generation capacity as one ages is associated with *sarcopenia* which is defined as a decrease in muscle mass and loss of function as a part of natural aging (40). The study of Lexell and others (1) stands out in the sarcopenia literature because it is made by direct measurement from cadavers rather than indirect measurements such as computational tomography or MRI in the evaluation of muscle mass. According to their study on 43 previously healthy male cadavers aged 15-83 years, the anatomical muscle surface area of the *vastus lateralis* muscle was found 10% lower in the age group of “51” (age range: 49-56, mean=51, n=8) than in the age group of “20” (age range: 15-22, mean=19, n=9). This decline accelerates from the age group of “70” (70-75 age range, 73 average, n=9) and reaches 40% loss muscle surface area in the age group “80” (80-83 age range, 82 average, n=8) (1). As a result of this loss of muscle mass and the decrease in the capacity of the muscles to exert force, compensatory movements, decreased movement speed and loss of balance are observed in daily activities of older individuals (for detailed information on the decrease in muscle quality as a result of aging and sarcopenia, see (50)).

Loss of muscle strength in aging individuals is not entirely related to loss of muscle mass. This suggests that neurological and other factors unrelated to muscle mass play a role in the development of age-related muscle weakness.

The Fall Risk in the Elderly

It has been reported that the most common postural problem in older individuals is weight transfer or erroneous displacement of center of gravity by the individual (51) which are at the same time the most common risk factors for a fall situation in elderly. Falls are the most serious cause of hip and wrist crackings or fractures and head injuries in older individuals (51).

The fact that the decreased postural control ability and postural balance due to advanced age negatively affect daily activities (52) and increases the risk of physical function loss, injury and loss of life (51, 52) as a result of the increased risk of falling (53, 54, 55, 56, 57) makes the protection and improvement of motor control and coordination mechanisms in aged people clinically important.

2.1.2 Effects of Exercise on Postural Control

Contrary to fine motor skills (58), balance skill is affected by exercise rather than hereditary i.e., genetic factors (59).

One of the two most important positive effects of regular and sustained physical activity/exercise on the postural control of aged people is the protection and the improvement of the balance ability (60, 61, 62), and the second is the decrease in proprioceptive decline (63, 64, 65). Regular and sustained physical activity/exercise achieves these by decelerating the decline of efficiency of several neural pathways responsible for postural regulations, and increasing nervous system functions, thanks to repetitive excitations of sensorimotor system (60, 61, 62). When the worldwide growth rate of the population over the age of sixty (United Nations, 2020) and the gradual decrease with age in participation in physical activity in the whole population (World Health Organization, 2020) is considered, understanding the effects of exercise on the postural control of aged individuals appears to be important.

Running

It is reported in the literature that “the motor repertoire and motor coordination efficiency” decrease with the effect of aging (although there are studies showing that the motor repertoire does not change with aging), while improve or their decline is prevented with the effect of regular exercise (both in young and older individuals). So, “aging” and “regular exercise” seems to have opposite effects on the motor repertoire (i.e., the number of muscle modes) and motor coordination efficiency (i.e., absence of co-activation pattern in muscle modes).

Running is a more applicable and sustainable form of physical activity compared to physical activities such as balance exercises (13) and dance (14), which have been shown to have positive effects on the preservation and development of motor coordination in healthy aged individuals. Running does not require a special trainer, partner, special equipment and can be done in both indoor and outdoor areas in a relatively flexible, accessible and inexpensive way. Regular running training improves lower extremity strength and endurance.

Although aerobic running effort is not a type of exercise that focuses directly on balance and coordination, it is a fluent, dynamic, rhythmic and complex sensorimotor activity that improves the ability to adapt to the environment posturally by constantly balancing internal and external perturbations.

According to a study (66) showing the positive effect of running on balance skills in older people, the postural oscillations observed during balancing movements performed with eyes open at different difficulty levels was similar in master runners over 60 years of age and young participants, while the oscillations were 4.5-8 times higher in the sedentary aged group compared to both master runner and young groups. Additionally, Power and others (67) reported that “functioning motor unit numbers”, which is an important factor causing sarcopenia and age-related motor performance decline when the number is low, is higher in master runners aged 60 and over than in the control group of the same age, and the same as in the young control group.

In summary, it is supported by the literature that in elderly individuals long-term and regular running exercises can improve somatosensory integration through decelerating the age-related decrease in muscle mass (68), improving neural drive to the muscles (69), protecting muscle strength and proprioceptive/kinesthetic sensitivity (70).

It is understood that regular running exercises are not limited to aerobic development, which is the output of exercise type, in aging people due to its above-mentioned effects on morphology and functions of neuromuscular system.

However, the effect of aerobic running effort on the neural control of multi-muscle coordination in aged individuals has not been studied. Therefore, this thesis study is based on the hypothesis that regular running exercises may contribute to the coordination between muscles/extremities and thus to the preservation/improvement of age-related neuromuscular control components.

2.2 Motor Control Theories in Postural Control

A motor strategy aiming to maximize the efficiency of motor movement during the execution of a particular motor task is chosen by an individual depending on the structural and functional constraints of his/her locomotor system. The identification of this motor strategy is claimed to be the way to understand the functional status of the individual (71).

2.2.1 Degrees of Freedom Problem

In the human body, there are more muscles than necessary to control the joints in the formation of a movement. Participation of muscles in contraction occurs with muscle activation, which occurs by stimulating many motor units at different frequencies. Therefore, humans must build their locomotor patterns based on an enormous number of variables because human locomotion requires the coordination of a great number of muscle activations and joint movements (72). The great number of muscles and joints to control during the task of controlling movement creates a problem of overabundant degrees of freedom.

It is suggested that this multi-joint and high-degree-of-freedom structure of the human movement system provides a large number of motor-equivalent solutions that can produce similar or functionally equivalent motor outputs for the realization of a motor behavior. Since there are many motor-equivalent solutions, there is no single correct or ideal motor pattern.

The existence of a large number of motor-equivalent solutions necessitates central nervous system (CNS) to make the right choices in criteria such as energy, stability and generalizability (73) among many possible paths for the human motor control mechanism (74). Because of the complex and non-linear relationship of muscle activity patterns with biomechanical functions, it may be difficult to find the ideal solution (75).

2.2.2 The Problem of Redundancy

The Problem of Redundancy (Tr., *Artıklık Problemi*), first defined by Bernstein (76), questions the strategies followed by the human motor control system while dealing with this a high degree of freedom complex control situation by providing the control of many variables.

2.2.3 Principle of Motor Abundance

In the following years, *Principle of Motor Abundance* (Tr., *Bolluk İlkesi*) was defined, based on the assumption that the high degree of freedom control situation facilitates the realization of the goal motor behavior by providing the large number of motor-equivalent solutions during natural actions (77).

2.3 Muscle Synergies Theory - Hierarchical Control of Movement

Gelfand and Tsetlin (78) suggest that multivariate neural organization of human movement system has a hierarchical structure. Accordingly, a neural organization receives input from a hierarchically higher neural organization and produces an output that will serve as input for a lower neural organization. At each control hierarchy level, the neural organization provides low variance (high stability) of the total output of that level.

Muscle Synergies Theory (Tr., *Kas Sinerjileri Kuramı*), also called *Hierarchical Control of Movement Theory* (Tr., *Hareketin Hiyerarşik Kontrolü Kuramı*), a strategy that is thought to simplify movement control by reducing the number of variables and high degrees of freedom that the CNS must control, accepts that the neural organization of the motor control mechanism is in a hypothetical two-level hierarchical structure (3). Accordingly, at the lower level (in the space of individual muscle activations), the human motor control mechanism reduces the degrees of freedom, alleviate *The Problem of Redundancy* and simplifies movement control by synchronous activation of selected groups of muscles, in patterns called *muscle modes* (Tr., *kas modları*), instead of controlling muscles individually i.e., instead of sending commands to each muscle separately (79, 80). In other words, in *Muscle Synergies Theory* it is accepted that the CNS may simplify the formation and control of movement by generating activation patterns common to specific muscle groups, rather than to individual muscles. These activation patterns describe the modular organization of movement. Therefore, it is suggested that the level of stimulation transmitted to the muscles controlled by the CNS as a group (muscle mode) or a change in this stimulation level will affect the activity level of all muscles in the muscle mode in the same way. Muscle modes reflect the presence of a common neural input to multiple muscles. According to the hypothesis, the CNS simplifies muscle control with modularity, using neural patterns to activate muscles in groups (81). Thus, complex movements are triggered by a single command input instead of detailed control signals (82).

At the theoretical upper level of hierarchical control, the processes of providing and maintaining the required motor output are controlled by changing the gains of the muscle modes participating in the movement (2, 3). Thus, at the theoretical upper level of hierarchical control, in order to produce the performance output with the least variability and high stability *muscle synergies* (Tr., *kas sinerjileri*) are created (3) with the neural organization of the muscle modes which fulfil the conditions i.e., to be specific to the movement, to work together in sharing and coordination, to compensate for each other's mistakes (83). Muscle synergies transform movement goals into biomechanical outputs by using muscle modes as building blocks that can be scaled and/or rearranged (9). Rather than constraining the CNS, the inherent stability of the muscle modes aids motor adaptation and motor learning (73) with the ability of muscle modes to be combined in various ways i.e., forming *muscle synergies.*

To sum up, in the two-level hierarchical structure of multi-muscle postural control, at the lower hierarchical level the individual muscles are organized into muscle modes, while at the upper hierarchical level the magnitudes of the muscle modes co-vary to produce the required action by the formation of muscle synergies. Muscle Synergies Analysis is frequently used in the analysis of human movements to understand the multi-muscle coordination (84, 85). The properties of muscle coordination during dynamic movements can provide important insight into the neurophysiological mechanisms of postural stability and synergistic control of motor performance. Thus, Muscle Synergies Analysis can provide this insight and identify differences in multi-muscle coordination of whole-body movements (86).

2.4 Muscle Modes in Motor Coordination

Ting and others (73) argue that muscle modes consist of neural plasticity in spinal and supraspinal structures, shaped by the continuity of biomechanical interactions with the environment.

Pre-defined (default) patterns of movement are formed in the embryonic process; in this process, spontaneous motor activities such as kicking and fluttering are observed (87). Human babies are born with the capacity to step and kick (88); movement patterns are refined with motor exploration (89) and more movement patterns continue to occur throughout development (90). Developmental process, motor exploration, experience and exercise play a role in shaping the individual's movement pattern (73).

It is argued that “good enough” solutions for motion may be found after several iterations of random research (91) and that once found, these solutions will be reinforced by use-related neural plasticity (73).

Muscle Modes in Development of Motor Coordination

Clark and others (85) report that experimental studies in postural control have shown that muscle activation patterns during locomotor and postural tasks may demonstrate a similar modular organization in animals and humans (84, 92, 93, 94, 95, 96, 97, 98). From an evolutionary point of view, it can be thought that the advantages that muscle modes provide to the movement generation and movement control system may have been transferred in the evolutionary process.

Learning the performance of a new movement is easier by changing the way a small number of muscle modes participate in the task, rather than learning new control strategies for individual muscles (73). Thus, from a biological standpoint, muscle modes reduce the cost of connecting neural networks while improving the speed, robustness, and adaptive capacity of motor exploration for new movement patterns (73, 99, 100). As muscle modes develop and refine throughout life, the costs of timing and energy are minimized, and accuracy and sharpness increase in movement (101, 102, 103, 104, 105).

Is the Formation of Muscle Modes Biomechanical or Neural?

It has been discussed whether muscle modes reflect neural control mechanisms or they occur from biomechanical constraints arising from skeletal muscle structure and function.

Because of the fact that despite different sensory states (106, 107), different biomechanical conditions (108, 109, 110, 111, 112, 113, 114) and different loading conditions (84, 115, 116), muscle modes are preserved throughout motor behavior, it is suggested that muscle modes reflect the structure of neural output (9).

Muscle Modes as an Individual-specific Indicator of Neuromuscular Control

Muscle modes are personalized movement-specific neuromechanical solutions that are shaped by evolutionary, developmental and learning processes (73). Consistent muscle modes are seen in the same individual under different biomechanical or kinematic conditions. Appearance of consistent muscle modes in different biomechanical conditions for an individual; reflects preferred patterns of modulated muscle coordination for different classes of movement, not instantaneous optimizations of muscle modes based on biomechanics. For example, the same muscle modes are used by an individual at different walking speeds and even when perturbations are encountered during walking (112, 117). Furthermore, it has been shown that the same muscle modes are used in the sit-to-stand movement performed at different chair heights (118) and at different speeds (118, 119). Professional dancers used similar muscle modes during walking on balance board and walking on floor, although they exhibited different movement kinematics through these two walking conditions having different difficulty levels in terms of balance. Thus, in postural control, muscle modes are preserved in different biomechanical configurations (73).

Nevertheless, muscle modes in postural control of a particular motor behavior under the same biomechanical or kinematic conditions may differ in structure and number among individuals (73). To illustrate, although similar movement kinematics were observed during walking on the narrow balance board in dancers and the sedentary control group, the muscle modes used by the two groups were different (9). Differences in the number and composition of muscle modes between professional dancers and the sedentary group cannot be explained by kinematic differences. Differences in muscle modes between dancers and sedentary groups reflect changes in neural control of movement as a result of years of training, not biomechanical constraints from movement or skeletal-muscular structure and function (9). Thus, the structure and number of muscle modes are predominately originated from individual-specific neural control mechanisms underlying movement, rather than movement kinematics or biomechanical conditions (120).

2.4.1 Number of Muscle Modes

It has been shown that complex human movements are simplified by a small number of muscle modes (84, 85) and that typically three or four muscle modes are used in one movement (121). It is accepted that the number of muscle modes gives an idea about the neuromuscular characteristics of the individual; specifically, the number of muscle modes is directly proportional to the motor repertoire size (9).

It is claimed that the high number of muscle modes used in performing a movement *i)* increases the richness of complex control in multi-muscle coordination by increasing the number of variables controlled by the CNS in parallel with the “Principle of Abundance” (122), *ii)* expands the motor action set (i.e., increases the motor repertoire size) by allowing the production of additional biomechanical functions, and *iii)* contributes significantly to balance (9).

The decrease in the number of muscle modes used during a particular motor task is interpreted as a decrease in the richness of complex control in multi-muscle coordination and as a numerical indicator of poor motor performance ability (85). Small motor repertoire size (low number of muscle modes) restricts the individual's ability to perform more complex movement tasks, such as walking with varying speed, stride length, or stride height (113).

In healthy young individuals, the number of muscle modes controlled by the CNS increases as the postural task becomes more difficult (122). For example, it has been observed an increase in the number of used muscle modes when exhibiting higher motor skills i.e., when voluntary body sway task is made challenging by perturbation or restriction of somatosensory information (122) and when switching from walking on the ground to walking on a narrow balance board (9).

On the other hand, in studies of motor disorders, it has been demonstrated that the number of muscle modes generally decreases, if the motor skill level decreases during walking as a result of stroke (85), spinal cord injuries (123, 124) or Parkinson's disease (125).

These findings suggest that individuals can strengthen their motor performance skills by increasing the number of muscle modes they control during challenging motor tasks, as long as they have a large enough motor repertoire; however, people with weak motor control show poor motor skills by using a low number of muscle modes due to the limited motor repertoire capacity.

The number of muscle modes has been the subject of scientific research in recent years, as exemplified above, as it gives an idea about the neural control of multi-muscle coordination in individuals.

Effect of Aging on the Number of Muscle Modes

In studies examining the relationship between aging and muscle modes, healthy young and older adults use the same number of muscle modes during the movements such as stepping to different step heights (126), voluntary body sway (127), sit-to-stand (119, 128). On the other hand, An and others (8), reported that the number of muscle modes used during sit-to-stand movement is three for young people and varies between one to three for older individuals.

In the aforementioned studies (8, 119, 126, 127, 128), the fact that there is no grouping of participants according to their physical activity levels and no information about their physical activity levels makes it difficult to interpret the findings regarding the variable number of muscle modes used by the younger and older groups in a particular motor task. The exercise histories of the aged participants in these studies mentioned above may have prevented or limited the possible age-related declines in their neuromuscular systems, and as a result, these aged participants may have used the same number of muscle modes as the younger ones.

Allen and Franz (6) showed that older adults without a fall history used the same number of muscle modes as young adults during walking. On the other hand, they showed that older adults, who have a fall history even though they do not have a clinically determined neurological problem, use fewer muscle modes than older individuals without a fall history and young adults. This finding is important in that it shows that the change in the number of muscle modes during normal aging may be closely related to the decrease in motor coordination and loss of balance.

In the same study, it is pointed out the potential of using the number of muscle modes as an indicator in clinical evaluations in determining the fall risks of elderly individuals without a certain neurological disease. In this respect, it is thought that studies on the determination of the number of muscle modes in aged groups can contribute to the existing knowledge in this field.

Effect of Exercise on the Number of Muscle Modes

There are studies pointing out that long-term and regular exercise provides a higher motor repertoire size (i.e., higher number of muscle modes). For example, Sawers and others (9) showed that young ballerinas who do long-term and regular exercise use higher number of muscle modes than the sedentary group during walking on a narrow balance board that requires balance skills, although both groups show similar movement kinematics during this walking.

Effect of Aging and Exercise on the Number of Muscle Modes

Due to the limitations in the literature of studies in which young and older adults are grouped as “physically active” and “sedentary” according to their physical activity levels, findings and comments on the effect of both age and regular exercise on the change of the number of muscle modes remain as inferences or assumptions.

In the study of Wang and others (14), one of the rare studies examining aging and muscle modes, it is reported that two groups consisting aged healthy adults (one group regularly dance and the other regularly walk) used the same number of muscle modes during preparation for stepping in response to support surface translation. The fact that there were only aged participants in this study, and there was no young or sedentary control group, does not allow to reveal the effects of age and exercise participation factors on the number of muscle modes.

2.4.2 Composition of Muscle Modes: Reciprocal and Co-activation Pattern

It is suggested that with a neural stimulation transmitted to a muscle mode involving more than one muscle, all the muscles included in the muscle mode are stimulated together. Both agonist and antagonist muscles of a joint can be in the same muscle mode. Depending on the stimulation of the agonist or antagonist muscles in the muscle mode, the muscle mode may exhibit a *reciprocal* or *co-activation* contraction pattern, that is, the composition of muscle mode.

In the *reciprocal* contraction pattern, the agonist muscles are activated while the antagonist muscles are inhibited. In the *co-activation* contraction pattern, the agonist and antagonist muscles are activated together. Co-activation modes correspond to parallel changes in the activation levels of antagonistic muscles of the same joint whereas reciprocal modes reflect coupling of dorsal or ventral muscles across different joints show parallel scaling of their activation levels. While reciprocal muscle modes contribute effectively to movement (14), co-activation observed muscle modes mostly aim to strengthen joint stability by simultaneously increasing the muscle tones of oppositely acting muscles in the joint in order to counteract interferences that threaten postural balance (129).

Rigid posture resulting from high muscle co-activation causes a decrease in joint mobility and flexibility of the movement (130, 131, 132, 133). This situation reduces the degree of freedom organized by the postural control system (134), restricts the production of compensatory postural responses (135, 136), reduces the efficiency of postural control (137) and negatively affects the movement economy (138). In summary, the muscle mode composition, that is, the reciprocal or co-activation pattern of the muscles in the muscle mode, reflects the efficiency of motor coordination (9). For example, the co-activation contraction pattern has an effect that reduces motor coordination efficiency (9).

The co-activation contraction pattern is seen more common in unstable conditions (139, 140), in people with neurological (141) or motor impairments (85, 123, 124, 142) and in older adults (10, 11, 12).

Effect of Aging on the Composition of Muscle Modes

In the study of Wang and others (12), it was reported that during voluntary body sway movement, older adults had more co-activation composition, while all young people exhibited a reciprocal composition in their muscle modes.

The increase in co-activation pattern in muscle modes as a result of natural aging process is interpreted as an adaptive postural reaction to compensate the decline in the ability to receive and process sensory inputs (10) and the decline in proprioception (46, 143). Among older individuals, higher muscle co-activation pattern is observed in those with weaker postural control (46, 144).

Effect of Exercise on the Composition of Muscle Modes

It has been shown that as a result of the practice of the given motor task (139) and regular exercise (9, 13, 14) the composition of the muscle mode is reorganized and the co-activation pattern turned into a reciprocal pattern; therefore, more efficient motor coordination is provided and motor performance is increased.

In studies involving healthy young adults, it has been reported that:

i) during a compelling balance task (i.e., load release task on unstable board), the individuals who used the co-activation pattern in the first attempts and failed in stabilization started to use the reciprocal muscle mode pattern after five days of practice of the given motor task by reorganization of their muscle modes, and their balance loss decreased (139),

ii) during walking on a narrow board, the muscle modes of young ballet dancers contain less co-activation pattern (thanks to years of motor exercise) than the young sedentary group's (9).

In studies involving healthy older adults, it has been reported that:

i) eight weeks of balance training reduced muscle co-activations in the ankle joint during postural control of dynamic movements, and additionally, improvements were seen in functional balance tests (13),

ii) the dancer group who has been dancing for the last five years used more reciprocal muscle mode pattern than the walking group during preparation for stepping in response to support surface translation (14).

In summary, co-activation pattern in muscle modes increases with aging (10, 11, 12) and decreases with exercise (9, 13, 14, 139).

2.5 Uncontrolled Manifold (UCM) Hypothesis

The Uncontrolled Manifold (UCM) hypothesis is based on the assumption that the CNS follows a control strategy focused on fewer control variables (muscle groups i.e., muscle modes) rather than each individual muscle involved in movement (145). The UCM hypothesis is described by defining elementary variables and *performance variables*. According to the UCM hypothesis, *elementary variables* are defined as degrees of freedom that can be changed independently of each other: e.g., joint angles or muscle activities (2). *Performance variables* are defined as the variables that are affected by the change of selected elementary variables that the neuromuscular system controls to ensure the successful realization of the motor task: e.g., center of mass (COM), center of pressure (COP), ground reaction forces or moments (2, 145). According to the UCM analysis, it is assumed that the neuromuscular system uses all available degrees of freedom in the space of elementary variables (e.g., joint angles or muscle activities) and provides stable but flexible control of performance variables (e.g., COM, COP, ground reaction forces or moments) (2). Thus, it is argued that the large number of degrees of freedom provides an advantage to the neuromuscular system during the correct performance of the motor task based on the *Principle of Motor Abundance* (2, 77).

2.5.1 Variance Components (V_{UCM} and V_{ORT})

According to the UCM hypothesis, the CNS selects a *manifold* (UCM) corresponding to the performance variable it will stabilize through the elementary variables (muscle modes) it controls, and tries to achieve and maintain the stabilization of this performance variable by changing the gains of the elementary variables (muscle modes) (146).

The CNS selectively limits the variability of muscle modes (in the direction orthogonal to the UCM subspace) that causes a change in the performance parameter it tries to maintain its stability, while allowing high variability of muscle modes in other directions. When the variance structure of the deviations observed in the control variables (muscle modes) is examined during multiple repetitions of a specific motor task, it is possible to analyze two variance components on the manifold (V_{UCM}) and orthogonal to the manifold (V_{ORT}). UCM analysis decomposes the between-trial variability in the elementary variables into variance within the uncontrolled manifold (V_{UCM}) and variance deviating from the uncontrolled manifold (V_{ORT}) (2, 145). In multiple repetitive measurements of the same motion, the variance orthogonal to the manifold (V_{ORT}) is expected to decrease, as opposed to the variance on the manifold (V_{UCM}). In other words, if changes observed in variance do not affect performance while maintaining an important performance variable, it is expressed as “good variance” (V_{UCM}) and if changes observed in variance affect performance during maintaining an performance variable, it is expressed as “bad variance” (V_{ORT}) (3). Good variance can be defined as “motor-equivalent solution” and bad variance can be defined as “non-motor-equivalent output” (17).

V_{UCM} is a numerical measure of how much the elementary variables co-vary to stabilize the performance variable around its mean. The V_{ORT} represents the number of elementary variables that destabilize the performance variable by deviating it from its mean.

2.5.2 Synergy Index

V_{UCM} / V_{ORT} ratio, which represents *muscle synergy*, expresses how much the neuromuscular system uses motor abundance to stabilize the performance variable (2, 145). V_{UCM} / V_{ORT} ratio is greater than 1 indicates that the variance of the elementary variables is organized to stabilize the performance variable around its mean through multiple repetitions (2). In other words, if the good variance is greater than the bad variance i.e., $V_{UCM} / V_{ORT} > 1$, it states that the variance stabilizing the performance variable is higher than the variance destabilizing the performance variable and it is deduced that the synergy between the muscles is high (2).

Figure 2.1 represents planar expression of the uncontrolled manifold approach. In this representation, a task is defined and 3 different possible variance structures are exemplified over this task to clarify the functions of variance components and the synergy concept. The task is to maintain a constant 40 N total force applied by the F1 and F2 effectors. The points shown surrounded by circles and ellipses represents the value of the applied total force in each trial. In this case, the forces applied by the F1 and F2 effectors and a constant 40 N total force can be defined as elementary variables and performance variable, respectively. Elementary variables (all the possible forces can be applied by the effectors) will try to stabilize the goal i.e., performance variable in each trial. In case that elementary variables work together in sharing and coordination and compensate for each other's mistakes (83) to maintain performance variable, it is defined as *synergy*.

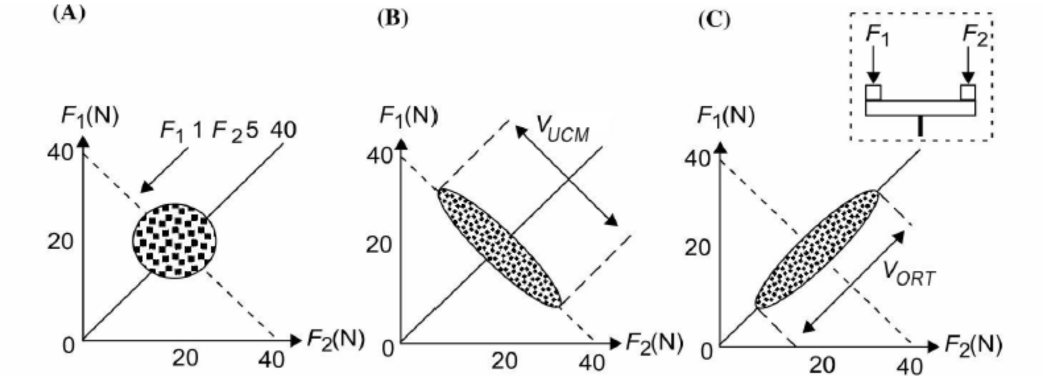


Figure 2.1 Planar expression of the uncontrolled manifold approach. Adapted from (3) page 122.

Figure 2.1.A shows a circular distribution such that both effectors performed above or below the total force in each trial without consistency. No synergy is observed between the two effectors, since they are not compensating each other's errors. In Figure 2.1.B, force distribution is elliptical. It is seen that two effectors work together to succeed the total value of 40 N and compensate for each other's error by increasing its value while the other’s value is below the average contribution, and vice versa. These conditions indicate *synergy* between the two effectors. In Figure 2.1.C, force distribution is also elliptical, but its position in the space is orthogonal to the ellipse in Figure 2.1.B i.e., orthogonal to the UCM subspace. Here, two effectors increase or decrease at the same time and do not exhibit the ability to compensate for each other's errors. So, their errors in the same sign add to each other and resulted with the total force values distant from 40 N.

Therefore, the larger variance on the UCM subspace (and the lower variance on the ORT subspace) indicates that the CNS provides coordination between the elementary variables without affecting the stability of desired performance variable, and indicates the existence and strength of the *synergy* between the elementary variables.

3. METHOD

This thesis study falls within the scope of descriptive research. The research has a cross-sectional type of noninvasive analytical method. The research was carried out in the *Neuromuscular Control Research Laboratory* (NMLab) by using its research infrastructure and physical facilities which is located within Hacettepe University Faculty of Sports Sciences, Department of Exercise and Sports Sciences, Division of Biomechanics and Motor Control. The methods and protocols used in the study were approved by the Hacettepe University Non-Invasive Ethics Committee (see Appendix 1 for Ethical Approval).

3.1 Participants

The research population consists of male and female healthy sedentary and runner individuals between the ages of 20-69 living in Ankara. The healthy young sedentary group (n=12) between the ages of 20-28, the healthy older sedentary group between the ages of 57-69 (n=12) and the healthy older trained (master runner) group between the ages of 57-66 (n=11) constitutes the sample of the research. Table 3.1 shows participant characteristics.

Table 3.1 Participant characteristics (mean ± SD).

Group	Gender	Age (year)	Stature (cm)	Body mass (kg)
Master Athlete (N=12)	Female (N=0) Male (N=12)	60.8 ± 2.9	173.6 ± 4.9	71.4 ± 5.9
Older Sedentary (N=11)	Female (N=2) Male (N=9)	62.6 ± 3.4	171.2 ± 10.0	75.0 ± 10.6
Young Sedentary (N=12)	Female (N=3) Male (N=9)	22.9 ± 2.0	174.0 ± 12.8	66.3 ± 12.4

3.1.1 Determination of Sample Size

In the previous studies examining muscle synergies in young and old groups (8, 119), small sample sizes were specified as 3 young, 7 older participants and 4 young, 3 older participants, respectively. In the literature, it is seen that the sample sizes are small for the studies that include multi-repetitive, multi-joint motions and biomechanical analysis of the data from multiple data acquisition sources. The sample size of this study was determined as 12 for each group by taking into account the selected error margin, the power of 0.80 for the estimated effect size reached in the previous studies on similar groups (12, 14, 80) and the expected average difference (sedentary/trained) with a pragmatic approach within the measurement possibilities and accessibility of participant candidates.

3.1.2 Determination of Age Ranges

In the previous studies in which the effect of exercise or training on the motor coordination of older individuals is examined, the lower age limit for those included in the "advanced age group" has been selected as 60 or close to 60 years of age. For example, in the study of An and others (8), the age range of the older group was 60-74 years of age; in the study of Yang and others (128) it was 58-75 years of age; in the studies of Wang and others (14, 16), the age ranges of the older groups were selected as 59-65 and 60-65 years of age. In this thesis study, the lower age limit of the older group was determined as 57 due to the difficulty of reaching active individuals with regular training history at advanced ages. When the number of registered members of Ankara running groups and those who participated in the Ankara marathon (2021) according to age groups were examined, it was considered that it would be advantageous to select individuals over the age of 57 in order to reduce the risk of not reaching the targeted sample size, especially for the older runner group. In the review article of Hunter and others (38), it is seen that individuals under the age of 30 who have completed adolescence are defined for the young group. So, the age range of the young group was determined as 20-28 years of age.

3.1.3 Defining and Selecting the Participants for the Runner Group

The runner group (the group doing regular aerobic running exercise) was chosen to represent the trained group of the research sample, because the runners are the athletes who can continue their regular training despite pandemic conditions thanks to the fact that running training can be done without the need for an indoor environment, equipment, partner or trainer. In the preliminary research, it was determined that the runners were one of the exceptional group of exercisers who were able to continue their training with special permission by issuing a license, despite the pandemic lockdown period. Therefore, master runners (in the age group of 57-70) continuing to participate in running trainings and active long-distance running competitions who meet the condition of "have been practicing running training for more than 3 years at least three times a week for at least 60 min per session" were included in this study.

"Training age" of the master runner group which is the year they have been continuing to participate in trainings and competitions without a major interruption (i.e., interruption more than 6 months) is presented in the descriptive characteristics table (Table 3.2). Furthermore, the running tempos of the master runners are determined as the running intensity scale according to the race distances and durations in the last road run they participated in, and are presented in the descriptive characteristics table (Table 3.2) as "training intensity scale".

Table 3.2 Descriptive characteristics of master athlete group for each subject.

#S	Training age (year)	Training intensity scale		
		10K	**21K**	**42K**
1	20	-	1 hr 24 min	3 hr 04 min
2	15	46 min	1 hr 53 min	-
3	7	50 min	1 hr 53 min	-
4	17	-	1 hr 40 min	3 hr 29 min
5	30	40 min	1 hr 41 min	-
6	20	52 min	1 hr 44 min	-
7	10	55 min	2 hr	-
8	10	42 min	1hr 34 min	3hr 20 min
9	25	51 min	1hr 52 min	-
10	39	-	2 hr 5 min	5 hr 15 min
11	39	54 min	2 hr 14 min	4 hr 14 min
12	12	46 min	1 hr 43 min	3 hr 47 min

"Training age" indicates the year the subject has been continuing to participate in trainings and competitions without a major interruption, "training intensity scale" indicates the race distances and durations in the last road run the subject participated in, 10K, 21K and 42 K indicate the race distances in km the subject participated in.

3.1.4 Where and How to Reach Participants

The master runners were reached by making an announcement including information message about the purpose of the research, data collection methods and potential risks and a contact number to the members registered in the running groups in Ankara. On the other hand, young sedentary adults and older sedentary adults were reached by sending an information message about the purpose of the research, data collection methods and potential risks and a contact number for those who want to participate to the research to people from work, family and friends.

3.1.5 Inclusion Criteria for Participants

Persons who do not meet the inclusion criteria were excluded from the study. The inclusion criteria are set out below:

- Having read the “Informed Consent Form” (see Appendix 3) and declared in writing that he/she participated in the research on a voluntary basis,
- Being between the ages of 20-28 or 57-70,
- Not having any neuromuscular, neurodegenerative, vestibular health problem; orthopedic disease that may cause movement disorder, symptomatic arthritis in the lower extremity, any disability,
- Not having a history of surgery, fracture or injury in the lower extremity; or history of fall in the past year,
- Not using any medication that affects the balance,
- Being able to do 5 sets of consecutive 5 repetitions of Sit-to-Stand motion with 3 minutes of rest between the sets without any support,
- Having a body mass index below 28,
- For the sedentary groups, being in the “inactive” category as a result of the International Physical Activity Questionnaire (IPAQ) short form questionnaire for at least last 3 years,
- For the trained group, having been practicing running training for more than 3 years at least three times a week for at least 60 min per session.

3.2 Data Collection Tools

The data collection tools to be used in the research were a force platform and a sEMG system. The data obtained with the force platform and sEMG system were recorded simultaneously. An 80-channel A/D data acquisition card (National Instrument, NI USB-6225) with 16-bit resolution was used for digital recording and synchronization of analog signals. LabVIEW 2018 (National Instrument) software program was used for recording data and providing feedback to the participants, and Matlab 2019b (MathWorks Inc, USA) software program was used in data processing and analysis. Both software programs are licensed by Hacettepe University. All of the data collection tools specified above were available in the laboratory where the research was conducted. The measurements performed during the experiments and the laboratory equipment used are explained below:

3.2.1 Measurement of Ground Reaction Forces and Moments

Ground reaction forces occurring in 3 orthogonal axes (F_x, F_y and F_z) and moments of forces (torques) formed around these axes (M_x, M_y and M_z) were recorded with the force platform (AMTI OR6-7-2000). Analogue signals which are collected at a sample rate of 2000 Hz were amplified through an amplifier and converted from analog to digital with an 80-channel 16-bit resolution A/D data acquisition card (National Instrument, NI USB-6225) and recorded on the computer. Figure 3.1 demonstrates the coordinate system of the force plate. While defining the positive directions of the coordinate system of the force platform, the x-axis is taken from posterior to anterior, the y-axis from medial to lateral, and the z-axis from superior to inferior (Figure 3.1). The displacement of the COP signal was calculated in real time and presented to the participants as visual feedback during the VBS movement (to be explained in detail in Experimental Method).

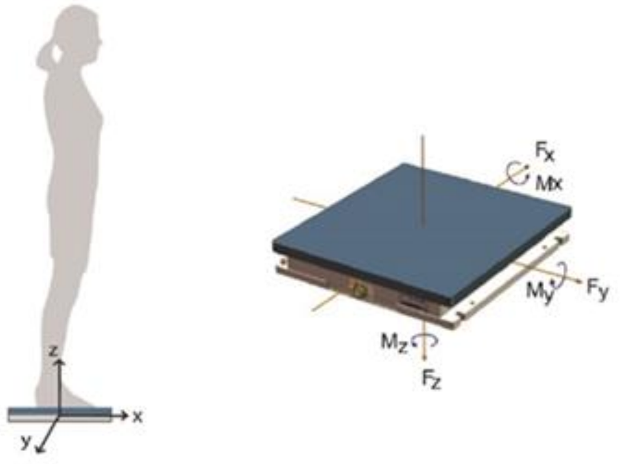


Figure 3.1 The components of the forces (F_x, F_y and F_z) and moments (M_x, M_y and M_z) measured on the force platform according to the coordinate system to be taken as the basis for the measurements where x, y, and z are the anterior-posterior, medial-lateral, and vertical directions, respectively.

3.2.2 Measurement of Muscle Activities

For sEMG measurements, a wireless sEMG measurement system was used (Delsys, Trigno) which has a single differential configuration with a frequency range of 20-450 Hz, a distance between electrodes of 10 mm and a fixed contact surface area of 50 mm^2. Muscle activities of 8 ventral and dorsal muscles effective in ankle and knee mobility including Tibialis Anterior (TA), Rectus Femoris (RF), Vastus Lateralis (VL), Vastus Medialis (VM), Gastrocnemius Medialis (GM), Soleus (SOL), Biceps Femoris (BF), Semitendinosus (ST) muscles were measured bilaterally (seen in Figure 3.4). In order to minimize the cross-talk effect, which is one of the most important problems experienced during sEMG recordings (147), superficial muscles with relatively large cross-sectional area were chosen for the measurement of muscle activities by sEMG method.

Skin preparation and electrode placement were performed according to the recommendations of SENIAM (*Surface Electromyography for the Non-Invasive Assessment of Muscles,* a European Union project aimed at high quality information exchange in the field of sEMG; see: (148). The surface area of each muscle of interest was shaved with a razor blade to get rid of dead skin and hair that are the factors that may cause noise in the sEMG signal. Then, this shaved area was wiped with alcohol with the help of a piece of cotton until a slight pinkness on the skin surface (to be helpful to get rid of dead skin). When the skin surface was dry, the skin preparation was completed.

Since the sEMG electrode placement is bilateral, it was necessary to determine the dominant side of the lower extremity. For this, each participant was given tests of kicking the ball (149) and climbing stairs. The foot, which is used to hit the ball and is cut off the ground first to step up, is considered dominant. The results of the two tests and self-reported dominant leg sides were congruent in all participants. Accordingly, the dominant foot was determined and the electrodes were placed with reference to this information.

sEMG electrodes were placed to the skin with an adhesive bidirectional anti-allergic tape (Delsys). Figure 3.2 demonstrates Delsys Trigno wireless sEMG measurement system. The activation graphs of each muscle (collected myoelectric signal for each muscle) is controlled in terms of signal quality and noise ratio. To do this, subjects were asked to perform a specific movement that activates each muscle of interest and during this movement, myoelectric signal of each muscle of interest monitored in real time by using LabVIEW program. In case of insufficient quality of sEMG signal or high noises, skin preparation and electrode placement steps repeated until handling expected sEMG signal features.

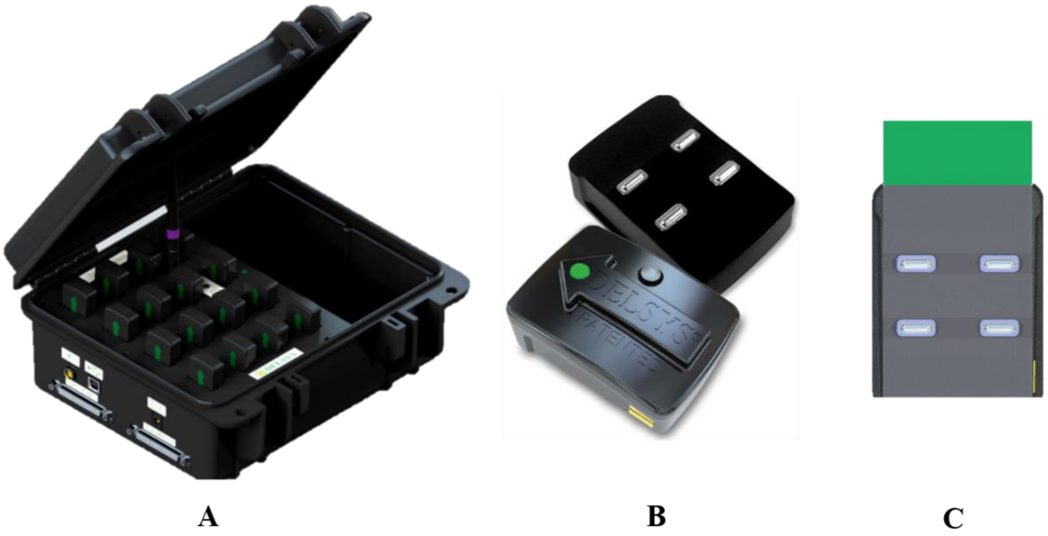


Figure 3.2. (A) Delsys Trigno wireless sEMG measurement system, (B) sEMG electrodes, (C) adhesive bidirectional anti-allergic tape.

Figure 3.3 demonstrates a representative scene of skin preparation for sEMG measurement and typical sEMG electrode placements for ventral muscles (TA, RF, VL, VM).

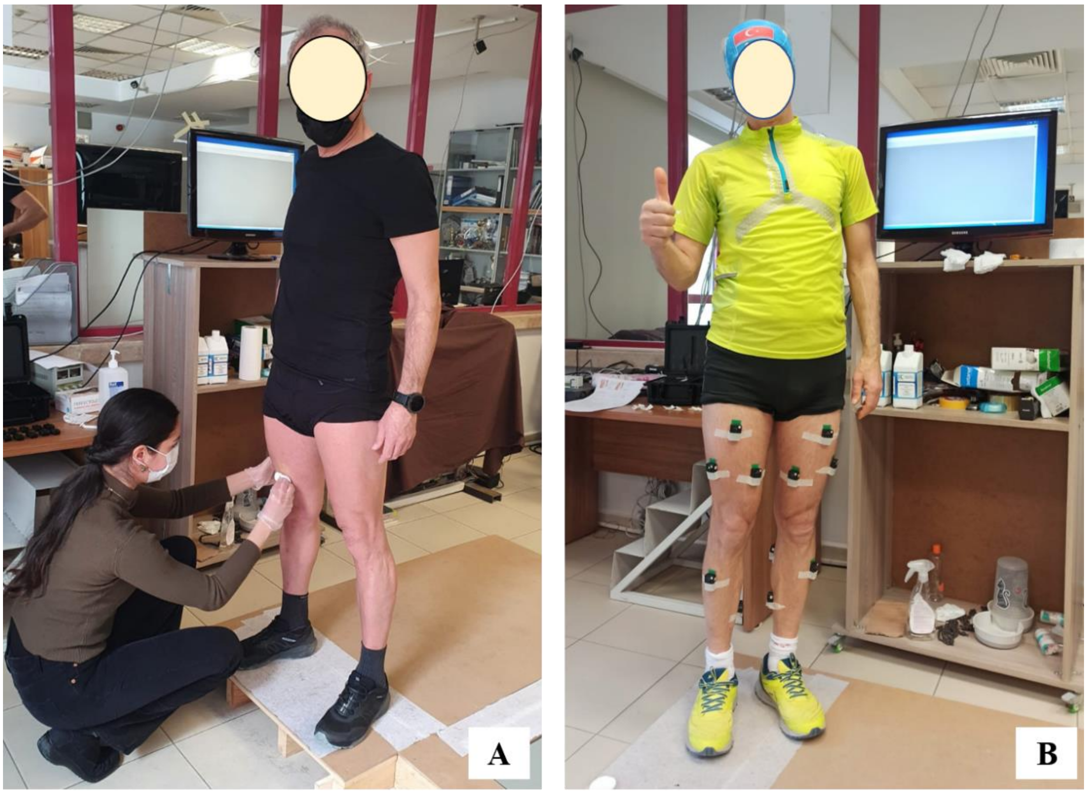


Figure 3.3. (A) Representative scene of skin preparation for sEMG measurement, (B) Representative sEMG electrode placements for ventral muscles.

3.3 Experimental Method

3.3.1 Selected Lower Extremity Movement

In this thesis study, which examines the lower extremity multi-muscle coordination of older individuals, it is aimed to reveal the effects of aging on the neuromuscular system effectively. It is known that the most contributing factor to the falling risk in advanced ages is the individual’s faulty performance of weight transfer or center of gravity displacement during dynamic movements (48, 49, 51),

By considering this fact and aiming to present a perspective to studies examining the daily life quality of older individuals, rather than athletic movements that require high power output such as weight lifting or cycling, a dynamic ecological daily-life movement “Voluntary Body Sway” (VBS) which requires the ability to shift the center of gravity in a controlled manner and allows motor diversity in the multi-muscle coordination is preferred as a lower extremity movement to investigate experimentally multi-muscle coordination of older individuals for this study.

Voluntary Body Sway (VBS)

VBS movement is a widely used method in the studies examining lower extremity coordination (12, 127, 150). It has been reported that the differences in VBS movement performance can be distinctive and descriptive in older adults in terms of their high or low fall risk (151). The motor strategies followed during VBS movement have generally been examined from kinematic and biomechanical perspectives in the literature rather than neuromuscular control perspective, although the neuromuscular mechanisms underlying the performance of this movement become more important, especially with aging. Therefore, neuromuscular mechanisms underlying the performance of VBS movement were aimed to examine in this study.

3.3.2 Experimental Protocol

All experimental measurements for each participant were completed in a single day and in a single session. For this reason, no measurement differences were observed for the same person, which may be due to the change of electrode location during the measurements. All measurements during the experimental protocol were made in healthy individuals with eyes open. During the protocol, participants with visual impairment were asked to wear the glasses or lenses they use in normal life. VBS movement demonstrated to the participants by performing it correctly by the person taking the measurement. Before data recording, the participants were given sufficient time to get used to the movement.

The collection of experimental data from the master runners was completed before the competition season in order to eliminate the effects of fatigue associated with the competition season. Moreover, in order to avoid the effect of fatigue, the master runners were asked not to train within the 24 hours before the measurement.

Voluntary Body Sway (VBS) Protocol

During Voluntary Body Sway (VBS) Protocol (80), while the participant was standing on a force platform in upright quite stance by wearing only socks but no shoes with both feet shoulder-width apart by keeping his/her hands crossed on the chest, he/she was asked to perform an inverted pendulum movement (forward-backward oscillation) between the extreme anterior and posterior postural positions within the safe limits, which can only be reached with the movement of the ankle joint. During the VBS movement, the participant was asked to prevent the movement of the hip joint or trunk and to maintain the position of his/her feet on the force platform, and not to disturb the connection of the soles of the feet and toes with the ground. The tempo of the VBS movement was determined by capturing the auditory rhythm given by the metronome (30 BPM, 0.5 Hz) at each extreme anterior position and each extreme posterior position (122). During the VBS movement, which is performed in a fluent and sequential manner, the same tempo (from the extreme anterior position to the extreme posterior position in 2 seconds) is provided for each participant. During the first 10 seconds of the VBS measurements, visual feedback was given to the participant about the real time COP position (86) using a 23-inch LED screen positioned at eye level at a distance of 2 m and he/she was asked to oscillate between his/her predetermined anterior and posterior limits. The purpose of this real time visual feedback of his/her COP position was to ensure the similarity of the intended oscillation interval (amplitude of M_Y shift) across repetitions and trials of VBS. He/she was also asked to keep oscillating between these limits after the end of the visual feedback till the end of the recording. In this way, the VBS movement was performed by the participant by keeping the gaze at eye level as 3 sets of 50 seconds with 2 minutes of rest between the sets. Each of the 50-second measurement was taken after the participant had started and acclimated to the VBS movement. During each of VBS trial, qualitative assessment was done through observation by the person taking the measurement in order to be sure about no inconvenient conditions such as any movement of head or limbs, speaking etc. requiring to stop the trial. Figure 3.4 shows schematic representation of the voluntary body sway experimental setup.

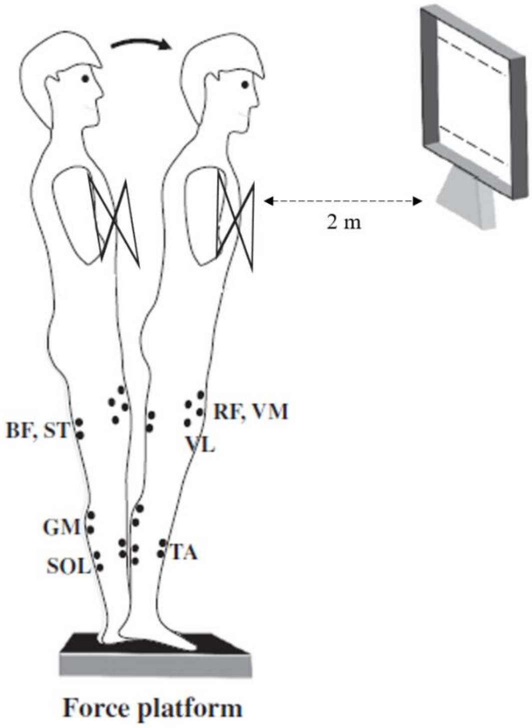


Figure 3.4. Schematic representation of the voluntary body sway experimental setup. The postural muscles which were bilaterally recorded during VBS protocol are also demonstrated. Ventral muscles: Tibialis Anterior (TA), Rectus Femoris (RF), Vastus Lateralis (VL), Vastus Medialis (VM). Dorsal muscles: Gastrocnemius Medialis (GM), Soleus (SOL), Biceps Femoris (BF), Semitendinosus (ST). Adapted from (152).

Phases of a Sway Cycle

Figure 3.5 shows the demonstration of a time normalized (0-100%) sway cycle and the phases of a sway cycle. Anterior (A) and posterior (P) peaks indicate the subject's maximum safe anterior and posterior sway locations, respectively. In Figure 3.5, A and P indicate anterior and posterior peaks, respectively. Each sway cycle starts and ends with anterior peaks. Between these anterior peaks, approximately around the 50% of the cycle the subject finds his/her posterior peak. Based on these motion pattern during each sway cycle, a sway cycle roughly divided into three phases in order to analyze the changes of V_{UCM}, V_{ORT} and ΔV (synergy index) variables during a sway cycle. Approximately 0-25% of a cycle is designated as "first anterior phase" where the subject moves from the first anterior peak to nearly orthogonal posture. Approximately 25-75% of a cycle is designated as "posterior phase" where the subject moves from nearly orthogonal posture, then finds the posterior peak and moves to nearly orthogonal posture again. Approximately 75-100% of a cycle is designated as “last anterior phase” where the subject moves from nearly orthogonal posture to the last anterior peak.

During a sway cycle, anterior and posterior peaks are accepted as the “difficult part” of the motion because these peaks contain anterior-to-posterior or posterior-to-anterior returns that require multi-muscular coordination to decelerate and accelerate properly.

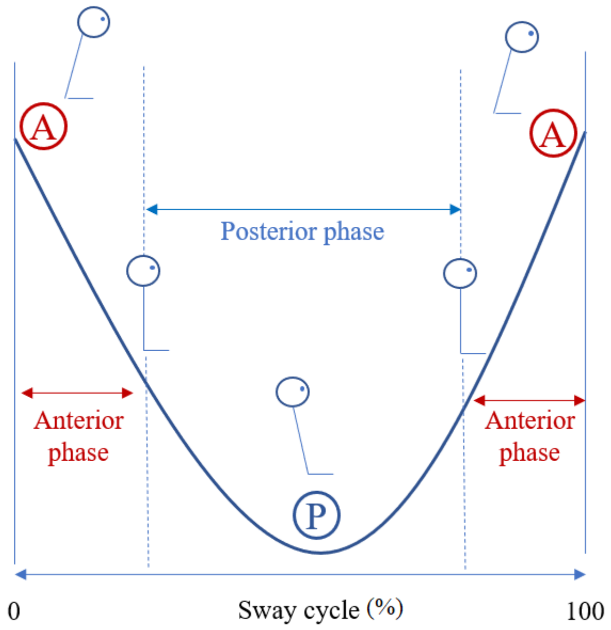


Figure 3.5 Time normalized (0-100%) sway cycle and sway phases demonstration. A and P indicate anterior and posterior peaks, respectively.

Reference Muscle Activity Measurements

Muscle activity measurements with sEMG needs to be normalized not only to be more consistent for the same person and the same muscle but also to be comparable between subjects and between muscles. Muscle activation data taken at rest and during submaximal contraction are included in this normalization process. Normalization makes the data more consistent for the same person in terms of removing possible noises in the collected myoelectric signal. Also, it makes the data comparable by eliminating factors such as variation in subcutaneous adipose tissue thickness or skin resistance and having different levels of maximal muscle contraction among individuals. This normalization method is used previous studies investigating muscle synergies (79, 80).

For the normalization process of sEMG data, muscle activation measurement of each participant was taken at rest for 10 seconds while the participant was lying on his/her back (supine position) by standing completely still and with all the muscles relaxed, not making any voluntary movements or speaking.

Furthermore, muscle activation measurement of each participant was taken during submaximal contraction for 10 seconds with two methods “*holding front load*” and “*holding back load*” (79, 80) for dorsal and ventral muscles, respectively. In holding front load trial, each participant was asked to stand quietly by holding a bar carrying a load, that is chosen by his/her among the loads of 10 kg, 7.5 kg and 5 kg, in front of the body while arms are fully extended at shoulder level and parallel to the ground. During holding front load trial, dorsal muscles are expected to be activated and sEMG record is expected to represent contraction of those muscles. Figure 3.6 shows a representative scene of holding front load trial.

In holding back load trial, each participant was asked to stand quietly by holding a bar, that is chosen by his/her among the loads of 10 kg, 7.5 kg and 5 kg, in front of the body while arms are fully extended at shoulder level and parallel to the ground. But, in holding back load trial, a load is carried by a pulley system in order to make the subject carry a back load while holding the bar in front of him/her. During holding back load trial, ventral muscles are expected to be activated and sEMG record is expected to represent contraction of those muscles. Figure 3.6 shows a representative scene of holding back load trial.

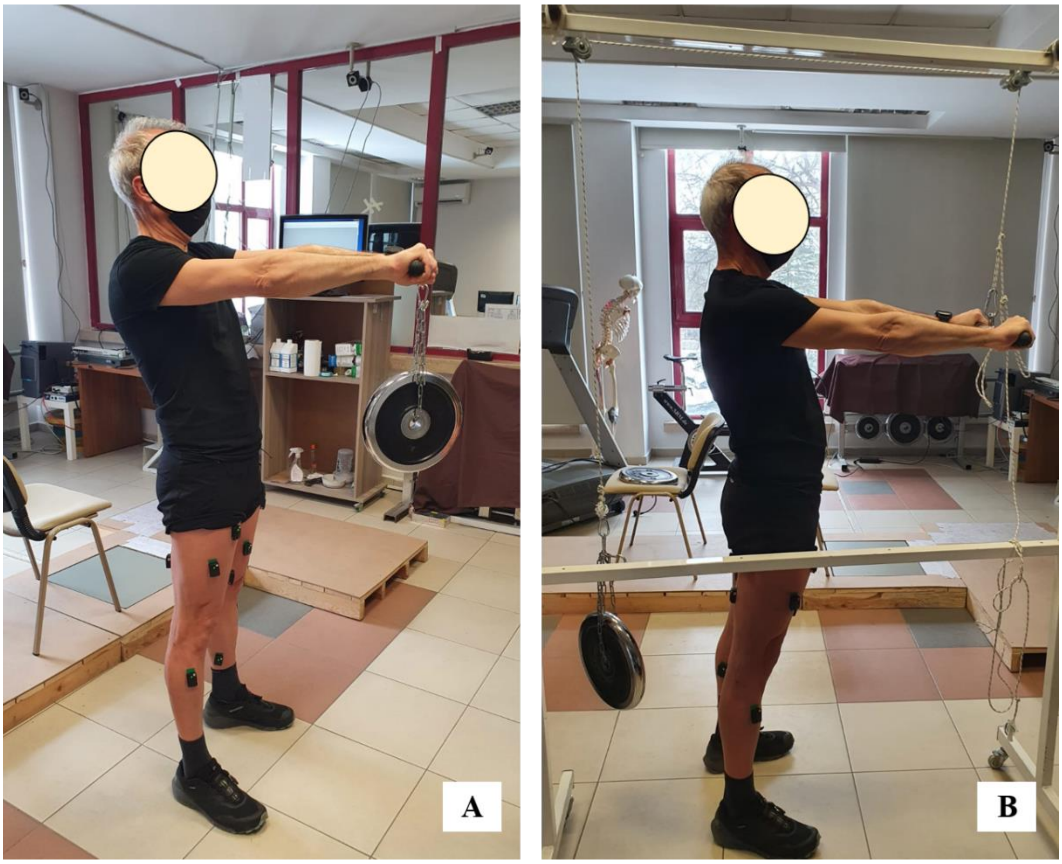


Figure 3.6 Representative scene of (A) holding front load trial, (B) holding back load trial.

Termination Criteria of Experimental Protocol

The criteria for terminating the experimental protocol were determined as follows:

- Statement of the participant participating in the research that he/she does not want to continue the research,
- The occurrence of health problems that would prevent the desired body movement during the experimental research (such as pain, ankle sprain, weakness, difficulty in breathing due to the mask),
- The occurrence of a technical malfunction in the measurement tools in the laboratory environment which would prevent the conduct of the research.

Measures Taken for the Pandemic

During the data collection process, the measures taken for the Covid-19 pandemic period were as follows:

- Covid-19 information notices prepared by our University and the Ministry of Health were posted at the entrance and inside the laboratory,
- Those who show symptoms that can be associated with Covid-19, such as high fever, dry cough, sore throat and shortness of breath, were not accepted for the experimental measurement,
- Participants were required to wear a mask continuously from entrance to exit from the building, as Covid-19 is transmitted by droplets (the mask can only be removed during measurements recording),
- Participants were asked to clean their hands with disinfectant each time they enter and leave the laboratory.
- During the experiments, only thesis students and thesis advisor and/or those who are in the role of researcher were able to be in the laboratory,
- Except for compulsory situations, 1.5 meters of social distance were constantly tried to be maintained,
- All surfaces that participants and researchers could touch were disinfected with alcohol beforehand,
- Eating and drinking were not allowed in the laboratory, except for water.
- The laboratory environment was constantly ventilated.

3.4 Signal Processing and Data Analysis

Matlab 2019b (MathWorks Inc, USA) software program was used in data processing and analysis. Signal processing and data analysis were carried out in four stages:

i) determination of performance parameter (kinetic analysis),
ii) basic and advanced processing of sEMG signals (signal processing and normalization of sEMG data.),
iii) determination of muscle modes (Principal Component Analysis, PCA),

iv) determination of the variance components (V_{UCM} and V_{ORT}) and synergy index (Uncontrolled Manifold, UCM Hypothesis).

3.4.1 Determination of the Performance Parameter (Kinetic Analysis)

In our study, which examined the coordination of multiple muscles during multiple repetitions of the VBS movement, the force and moment outputs of the movement and the muscle activations during the movement were recorded simultaneously with the force platform and eEMG system, respectively. The force/moment output of the movement is needed to be used in order to divide successive, multiple repetitions of the VBS movement into sway cycles (each sway cycle starts and ends with anterior peaks and in the middle of the cycle there is the posterior peak, see Figure 3.5 for the phases of sway cycle) and exactly match them with the muscle activations occurring during the cycles.

Furthermore, UCM hypothesis is based on the idea that muscle synergies occur during multiple repetitions of a movement to keep the motor output constant for each repetition. The mentioned multi-repetitive motor output is called the performance variable (performance parameter). Performance parameter can be force, moment or COP outputs recorded during motion. In this study, the moment of force around the x-axis (M_Y) magnitude-time profile was chosen as the performance variable (performance parameter) that exhibits stereotypical behavior for each repetition of the VBS movement corresponding to each sway cycle.

The “sway cycle” for VBS movement (one voluntary body sway cycle) is defined as an oscillation from Anterior to Anterior in the magnitude-time graph of M_Y which also corresponds to the time period between two consecutive peaks of the magnitude-time graph of M_Y. For our data analysis, each sway cycle is an analysis window. In order to find the peaks of M_Y in the magnitude-time graph of M_Y, M_Y signal was temporarily filtered at 0.5 Hz with a zero-lag 2nd order Butterworth low-pass filter and the standard peak finding function (*findpeaks*) was used in the Matlab program. The two consecutive peaks of M_Y corresponds to the start and the end times of each sway cycle.

In the VBS movement protocol, the tempo given to each subject from anterior to posterior was 30 BPM, 0.5 Hz, i.e., 2 seconds. Thus, one ideal sway cycle which is from Anterior to Anterior should last 4 seconds. Since our sampling frequency was 2000 Hz (i.e., 2000 data point collected per a second), the length of one ideal sway cycle should be 8000 data point. For all subjects and all trials, each sway cycle length was calculated and those who exceeded 10% of error margin were excluded from the data set.

The start and the end times of each sway cycle was used in the temporal normalization process of performance parameter. All sway cycles were normalized by using 101 points so that the total time of the analysis window (sway cycle) was 100% movement cycles, and the analysis window was brought to the standard length.

The raw M_Y signal was actually filtered at 10 Hz with a zero-lag 2nd order Butterworth low-pass filter. Finally, M_Y data of all accepted sway cycles in all trials for each subject merged and a matrix of performance variable for each subject was handled. Representative filtered and time normalized M_Y time profile during a voluntary body sway trial is shown in Figure 3.7.

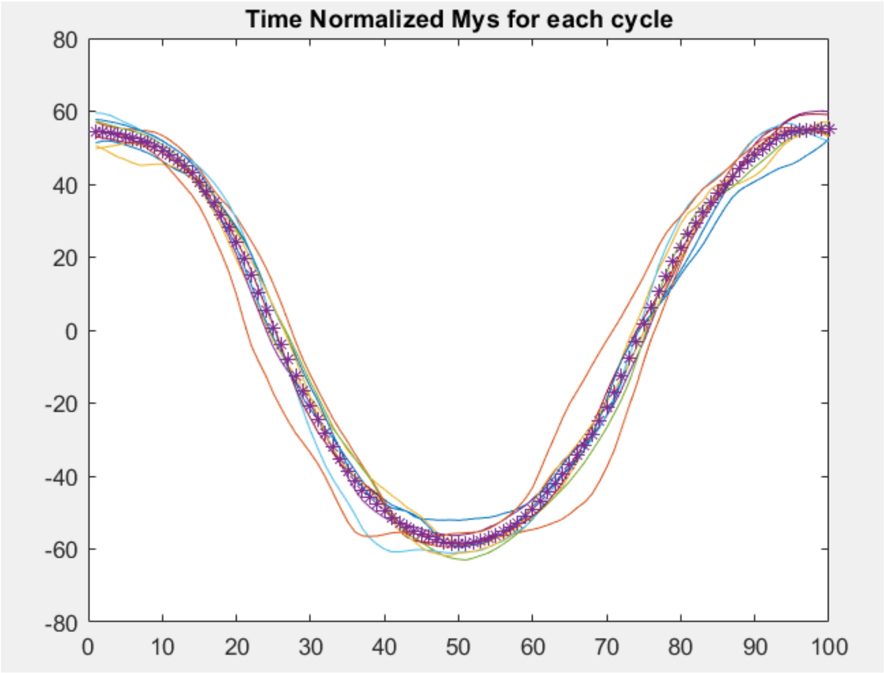


Figure 3.7 Representative filtered and time normalized M_Y time profile during a voluntary body sway trial. “*” line represents the mean of the all M_Y lines.

Calculation of Mean Sway Range

Mean sway range in AP direction is calculated for each subject of the three groups. Moment in mediolateral direction (M_Y) is equal to the subject's weight multiplied by the displacement in the AP direction (d_x) as seen in Equation 3.1. During voluntary sway, M_Y graph forms successive anterior and posterior peaks. Mean sway range in AP direction is the mean distance between these anterior and posterior peaks. So, anterior and posterior peak values of M_Y graph of voluntary sway motion are calculated and the mean distance between these peaks are divided to subject's mass and gravitational acceleration to find mean sway range in AP direction.

$$M_Y = m * g * d_x \tag{3.1}$$

3.4.2 Basic and Advanced Analysis of sEMG Signals

This step includes signal processing and normalization of sEMG data. The peak values of M_Y in the magnitude-time graph of M_Y was also used in the temporal normalization process of sEMG signals. sEMG signals corresponding to the analysis window determined as one VBS movement cycle were determined for each muscle and normalized to be 100% of the sway cycle duration so that the analysis window was brought to the standard length for sEMG signals as well. The raw sEMG signal was filtered at the range of 20-350 Hz with 2nd order, zero-lag band-pass Butterworth filter and the absolute value of the obtained filtered signal was taken. Then, the integrated EMG (iEMG) data were obtained by taking the numerical integral with respect to time at each 1% slice interval of the sway cycle.

For all subjects, all trials and all muscles, iEMG data were graphed and visually inspected. If any muscle activation signal abnormality was seen, which may had been overlooked during the measurement, resulting from loss of balance or incorrect application of the movement, that sway cycle was removed from the data set.

As in the previous studies investigating muscle synergies (79, 80), the normalization of sEMG signals was applied. By removing possible noises in the collected myoelectric signals and eliminating factors such as variation in subcutaneous adipose tissue thickness or skin resistance and having different levels of maximal muscle contraction among individuals, this normalization method makes iEMG indices comparable across muscles and subjects (80). Muscle activation data taken at rest and during submaximal contractions (see section 3.2.2 *Experimental Protocol*). Muscle activation data taken at rest and during submaximal contractions were also filtered at the range of 20-350 Hz with 2nd order, zero-lag band-pass Butterworth filter, then rectified and integrated. Mean values of integrated muscle activation data taken at rest ($iEMG_{Rest}$) and during submaximal contractions ($iEMG_{Ref}$) were used as normalization factors in the sEMG normalization process. Formula 3.1 shows the calculation of normalized iEMG indices by using normalization factors. As shown in Formula 3.2, resting muscle activities ($iEMG_{Rest}$) of each muscle were extracted from the iEMG indices of the relevant muscle belonging to each sway cycle calculated ($iEMG_{SC}$) and the result ($iEMG_{SC}$ - $iEMG_{Rest}$) was divided by the $iEMG_{Ref}$ data of the relevant muscle (ventral muscles divided by the $iEMG_{Ref}$ data obtained from “holding back load trial”, dorsal muscles divided by the $iEMG_{Ref}$ data obtained from “holding front load trial”, see section 3.2.2 *Experimental Protocol*). At the end of this process, normalization was performed for each muscle separately and the $iEMG_{Norm}$ matrix was obtained.

$$\mathrm{iEMG_{Norm}} = \frac{\mathrm{iEMG_{SC}} - \mathrm{iEMG_{Rest}}}{\mathrm{iEMG_{Ref}}} \tag{3.2}$$

Finally, $iEMG_{Norm}$ data of all accepted sway cycles in all trials for each subject merged and a matrix of $iEMG_{Norm}$ data for each subject was handled.

3.4.3 Determination of Muscle Modes (Principal Component Analysis, PCA)

Principal Components Analysis (PCA), as a statistical size reduction method, was used to determine the muscle modes by reducing calculated iEMG time series to muscle groups acting in conjunction with each other i.e., muscle modes. The number of muscle modes and the composition of muscle modes (co-activation level) were determined accordingly (see section 4.1 *Number of Muscle Modes* and 4.2 *Composition of Muscle Modes*).

The dataset used for PCA must have normal distribution. For this study, the data to be investigated by applying PCA is integrated EMG signals (i.e., $iEMG_{Norm}$ matrix) for each muscle of the subjects collected during the repetitive VBS motion. Therefore, z-scores of $iEMG_{Norm}$ matrix were computed by *zscore* function of Matlab program. Z-Score is a score representing how many SD away from the mean. Distribution of z-scores has zero mean and one SD. By computing z-scores of $iEMG_{Norm}$ matrix, the **correlation matrix** of $iEMG_{Norm}$ matrix was handled to work with it in PCA.

So, PCA was performed with the correlation matrix obtained from the $iEMG_{Norm}$ matrix with 8 columns representing the examined postural muscles and the number of sway cycle included in the analysis times 100 rows (each 100% sway cycle contains 100 rows of data points corresponding to 1% time windows). To illustrate, the dimensions of $iEMG_{Norm}$ matrix would be 8 columns and 3200 rows for the examination of 8 muscles while the number of sway cycle included in the analysis is 32. PCA was perform by pca function in Matlab program. By default, *pca* function in Matlab centers the data and uses the "*Singular Value Decomposition*" (SVD) algorithm.

PCA was yielded **Eigenvectors** and **Eigenvalues**. Eigenvectors are the principal component coefficients, also known as loadings. Eigenvectors matrix is a square matrix i.e., the dimensions of Eigenvectors matrix were 8 columns and 8 rows in case of investigating 8 muscles. Each column of Eigenvectors indicates a principal component and the rows contain coefficients for each principal component, and the columns are in descending order of component variance. Eigenvalues are the variances of principal components. The dimensions of Eigenvalues matrix were 8 columns and 1 row in case of investigating 8 muscles. Since eigenvalues are the variances of principal components, square root of eigenvalues is equal to SD of principal components.

Factor loadings matrix was obtained by multiplying Eigenvectors matrix and a square diagonal matrix with the elements of square root of eigenvalues matrix on the main diagonal. Factor loadings (8 columns and 8 rows) gave the correlation of the eigenvectors with the individual muscle components. The factor loadings are orthogonal to each other.

The number of principal components expecting to explain more than 70% of the variance between the repetitions in the $iEMG_{Norm}$ data for each participant was determined as 4 (see section 4.1 *Number of Muscle Modes*). In order to facilitate the principal component's dimension reduction, one of the orthogonal axis rotation methods, **Varimax rotation** method was applied by *rotatefactors* function in Matlab. So, rotated factor loadings matrix and rotated principal components (eigenvectors) matrix were obtained. The dimensions of rotated factor loadings matrix and rotated principal components matrix were 8 columns and 4 rows where 8 represents the examined muscles and 4 represents the number of principal components.

Muscle modes matrix (M-Mod matrix) was obtained by multiplying $iEMG_{Norm}$ matrix and rotated principal components matrix. M-Mod matrix has 8 columns representing the examined muscles and the number of sway cycle included in the measurement times 100 rows (each 100% sway cycle contains 100 rows of data points corresponding to 1% time windows). Finally, **Percent Varimax**, percent of variance that can be explained by 4 principal components (PCs) after varimax rotation, was calculated from the ratio of sum of the variances of 4 PCs (i.e., sum of first 4 eigenvalues) to sum of total variances.

3.4.4 Determination of Muscle Mode Composition

By determining the muscle modes by applying PCA, whether reciprocal or co-activation strategies are used in the generation of movement can be determined (153). Across young and elderly subjects, we searched for two types of PCs (muscle modes) based on muscles that loaded significantly (if absolute loading factor is over 0.5; (153)) which are *reciprocal* or *co-activation* muscle modes.

Co-activation muscle mode was detected if antagonistic muscle pairs were significantly loaded on the same PC with the same sign (16, 139) for ankle (TA vs. SOL and GM), for knee (RF, VL, VM vs. BF, ST, GM) and for hip (RF vs. BF, ST). Co- activation muscle modes are classified as ankle, knee and hip co-activation and based on included muscles to this study, these co-activation definitions are listed below:

i) **ankle *co-activation***: the ankle dorsiflexor muscle (TA) and one or all of the plantar flexor muscles (SOL, GM) coexist as significantly loaded with the same sign on the same PC,

ii) **knee *co-activation***: some or all of the knee extensor muscles (RF, VL, VM) and some or all of the knee flexor muscles (BF, ST, GM) coexist as significantly loaded with the same sign on the same PC.

iii) **hip *co-activation***: the hip flexor muscle (RF) and one or all of the hip extensor muscles (BF, ST) coexist as significantly loaded with the same sign on the same PC.

Muscle mode compositions other than these conditions, that is, the cases where agonist and antagonist muscles effective in the same joint were not seen to be loaded together with the same sign on the same PC were evaluated as ***reciprocal muscle mode***.

3.4.5 Determination of Synergy Index (Uncontrolled Manifold, UCM Analysis)

The Uncontrolled Manifold, UCM analysis was used to determine the variance components (V_{UCM} and V_{ORT}) and synergy indexes.

Uncontrolled Manifold hypothesis is based on the idea that the motor control system uses and arranges a set of elemental variables in order to stabilize a performance parameter (145). In this study, muscle modes are elemental variables that are manipulated by the CNS to stabilize the value or the time profile of M_Y as the performance parameter. Therefore, in this part of the analysis, our aim is to analyze the variance structure in the muscle modes for each sway cycle. To do this, first of all the derivative of muscle modes matrix (M-Mod) "ΔM-Mod" and the derivative of M_Y "ΔM_Y" was calculated in order to find the difference between the consecutive data points. According to UCM hypothesis, ΔM_Y is stabilized by co-variation of ΔM-Mod. So, a linear regression model is set between M-Mod and M_Y variables. Multiple linear regression analysis was used for each sway cycle to determine the relationship between time-dependent variability of M-Mod and M_Y variables, as shown in Formula 3.3 where k_i represent the coefficients of regression equation. The Jacobian Matrix was created with the coefficients of the regression equation (k_i) that is shown in Formula 3.4 where T represents the transpose of the matrix.

$$\Delta M_Y = k_1 * \Delta\text{M-Mod}_1 + k_2 * \Delta\text{M-Mod}_2 + k_3 * \Delta\text{M-Mod}_3 + k_4 * \Delta\text{M-Mod}_4 \qquad (3.3)$$

$$\mathrm{J} = [\mathrm{k}_1\ \mathrm{k}_2\ \mathrm{k}_3\ \mathrm{k}_4]^{\mathrm{T}} \qquad (3.4)$$

It is aimed to determine the synergy index with good (V_{UCM}) and bad (V_{ORT}) variance components according to the UCM hypothesis. V_{UCM} is the variance maintaining the value of performance parameter stable that is consistent and reproducible from cycle to cycle. V_{ORT} is the variance orthogonal to V_{UCM} that leads changes and does not contribute the stability of the performance parameter. Since the model between M-Mod and M_Y variables is linear, ΔM-Mod matrix is demeaned by subtracting the mean ΔM-Mod values for each cycle from each computed ΔM-Mod value. $\Delta\text{M-Mod}_{\text{demeaned}}$ matrix was handled with these residual values of ΔM-Mod matrix. The UCM was calculated as a set of all vector solutions x of a system of equations Jx = 0 which is the null space of the corresponding J matrix. The UCM linear subspace (f_{UCM}) is estimated according to Jacobian null-space. The orthogonal subspace (f_{ORT}) is the surface perpendicular to the f_{UCM}. V_{UCM} and V_{ORT} variance components are decomposed by the projection of ΔM-Mod's to these subspaces. The good and bad variance and total variance between trials in both subspaces are normalized according to the degrees of freedom (n-1) of that subspace (Formula 3.5, 3.6 and 3.7). Abbreviations used in the formulas; N: number of trials, n: number of dimensions (4 dimensions in the UCM subspace), d: the number of constraints (1 dimension in the ORT subspace).

$$V_{UCM} = \sigma_{UCM}^2 = \frac{1}{(n-d)N} \sum_{i=1}^{N} \frac{1}{(n-d)} f_{UCM}^2 \qquad (3.5)$$

$$V_{ORT} = \sigma^2_{ORT} = \frac{1}{dN}\sum_{i=1}^{N}\frac{1}{(n-d)}f^2_{ORT} \tag{3.6}$$

$$V_{TOT} = \sigma^2_{TOT} = \frac{1}{nN}\sum_{i=1}^{N}\frac{1}{(n-d)}(\Delta \mathrm{M\_Mod}_{demeaned}) \tag{3.7}$$

The synergy index (ΔV) was calculated to determine to what extent the variance observed between trials was due to the maintenance of the performance parameter (Formula 3.8). V_{UCM} and V_{ORT} were normalized by total variance to allow comparison between trials and participants.

$$\Delta V = (V_{UCM}-V_{ORT})/V_{TOT} \tag{3.8}$$

3.4.6 Lower Limb Laterality on Muscle Synergies

Studies investigating muscle modes or muscle synergies mostly have been carried out on muscles on the dominant side of the body so far (46, 80, 86, 118, 119, 122, 154, 155, 156). Else, in the study of An and the others (8), bilateral muscle activity measurements were taken, but right-left comparison was not made, and the muscle activation data from the right and left were averaged to represent a single muscle. In all these mentioned studies, differences in multi-muscle coordination between right and left (dominant vs. non-dominant) were neglected.

Peters (7) defined *lower limb laterality* in 1988 by emphasizing the different roles of the lower limbs on motor control i.e., “role differentiation of the feet”. According to Peters, the preferred (dominant) and the non-preferred (non-dominant) limbs have their own specific roles on *motor execution* and *stability*, respectively. In other words, the mobilizing or manipulating (role of *motor execution*) limb is the dominant foot, whereas the foot that is used to support the actions (role of *stabilizing*) of the preferred foot is the non-dominant limb.

Voluntary sway is a movement requires continuous bipedal symmetrical coordination of lower extremity. According to this “*motor execution*” and “*stabilizing*” role categorization of the dominant and non-dominant sides of the lower limbs, we thought that multi-muscle coordination that we investigate in this study could differ between the two sides of the lower limbs. Therefore, we wanted to compare dominant and non-dominant lower extremity multi-muscle coordination in terms of Muscle Synergies Analysis. Hence, non-dominant pairs of 8 lower extremity muscles “TA, RF, VL, VM, GM, SOL, BF, ST” were also subjected to PCA and UCM analysis to compare the results of muscle synergy analysis (variance components and synergy index) of the dominant side (8 muscles) and the non-dominant side (8 muscles).

In addition, we wanted to examine lower extremity coordination as an entire two-sided neurophysiologically-binded system during VBS movement. So, bilaterally chosen 8 lower extremity muscles “TA, RF, VL, VM, GM, SOL, BF, ST” (16 muscles in total including dominant and non-dominant pairs together) of each subject were also subjected to PCA and UCM analysis to compare the results of muscle synergy analysis (variance components and synergy index) of the dominant side (8 muscles) and the non-dominant side (8 muscles) with the results using two-legs-together (16 muscles).

During the experimental measurements, 3 sEMG electrodes lost their function and became unusable. In the remaining measurements, the number of electrodes on the non-dominant side was reduced. Therefore, subjects whose sEMG measurements could be taken with all 8 muscles on the non-dominant side were included in this part of the analysis. Thus, the number of participants for this part of the non-dominant analysis is 10 for young sedentary group, 11 for master athletes, and 5 for older sedentary group.

3.5 Statistical Analysis

The dependent variables of this thesis study were:

- the number of muscle modes
- the composition of muscle modes i.e., level of co-activation
- variance components (V_{UCM} and V_{ORT})
- synergy index.

The independent variables of this thesis study were:

- age (young x aged)
- participation in exercise (sedentary x trained)

SPSS 28 package program was used in statistical analysis. Between group comparisons for V_{UCM}, V_{ORT} and ΔV (synergy index) conducted by a non-parametric method, Kruskal-Wallis test since V_{UCM}, V_{ORT} and ΔV dependent variables did not satisfy parametric assumptions as a result of Shapiro-Wilk test for normal distribution and Levene's test for variance homogeneity between dependent variables. In case of the significant result of Kruskal-Wallis test, further statistical analysis conducted with Mann-Whitney U test as a Post hoc analysis. Statistical significance level was accepted as $p<0.05$.

4. RESULTS

In this chapter, the findings of the thesis study are presented in line with and in order with the hypotheses and research questions of the thesis that are included under the section 1.4 *Hypotheses and Research Questions*.

iEMG indices of 8 skeletal muscles “TA, RF, VL, VM, GM, SOL, BF, ST” which belongs to the ***dominant side*** of the lower extremity during one sway cycle of voluntary body sway motion of one typical subject for the three participant groups are shown in Figure 4.1.

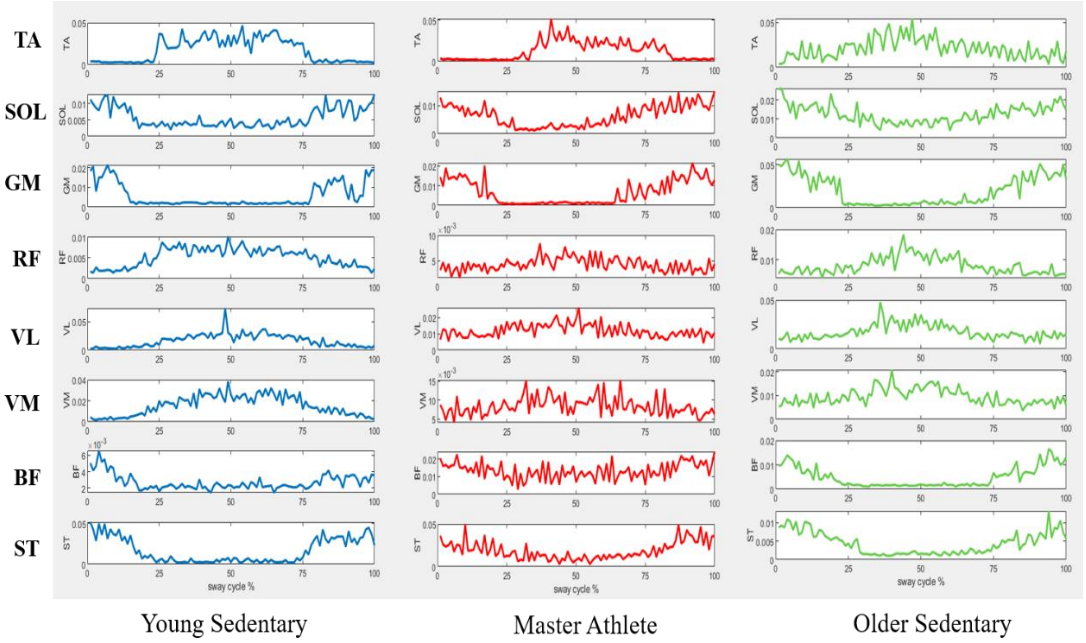


Figure 4.1 iEMG indices of 8 skeletal lower extremity muscles examined in this study during one sway cycle of voluntary body sway motion for one typical subject of the three participant groups.

Figure 4.1 shows that each typical subject of the three groups represented similar and expected muscular activity during one sway cycle of VBS such that the activity of ventral muscles (TA, RF, VL, VM) increased in the posterior phase and the activity of dorsal muscles (GM, SOL, BF, ST) increased in the anterior phases (see Figure 3.5 for the phases of the sway cycle).

In this part of the study, iEMG indices of 8 lower extremity muscles “TA, RF, VL, VM, GM, SOL, BF, ST” which belongs to ***dominant side*** of the lower extremity of each subject are subjected to Principal Component Analysis (PCA) to investigate modular organization of the dominant side of the lower extremity coordination during VBS movement. Each principal component (PC) represents the muscle mode as a component of modular motor control system.

4.1 Number of Muscle Modes

PCA conducted to reveal the adequate number of principal components to explain more than 70% of the variance of the repetitive voluntary sway movement. Figure 4.2 shows the line graph (scree plot) of the percentage of variance explained by each principal components for the dominant side of the three groups. It is seen that there is a similar trend among the three participant groups in terms of the percentage of variance explained corresponding to each PC during VBS motion. The scree plot shows that there is a sharp decrease in the percent of variance explained after the third principal component (PC) for all three participant groups. Moreover, the sum of the percent of variance explained corresponding to first three principal components (PCs) are more than 70% of the variance of the repetitive VBS movement for the dominant side of all three participant groups. Therefore, this means that the repetitive VBS movement can be explained by at least 3 principal components (PCs) for all participant groups: young sedentary group, master athletes and older sedentary group. However, the first 4 principal components (PCs) were selected to analyze. In the section 4.4 *Effect of Lower Limb Laterality on Muscle Synergies,* there will be comparisons of the results of muscle synergies analyses (UCM variance components and synergy index values) among the dominant side of the lower extremity, the non-dominant side the lower extremity and two-leg-together (16 muscles) conditions (see section 4.4 *Effect of Lower Limb Laterality on Muscle Synergies* for detail). The reason why the first 4 principal components (PCs) were chosen for the analysis is that the two-legs-together (16 muscles) condition does not satisfy the term to explain more than 70% of the total variance if the first 3 PCs are selected, and the above-mentioned condition is met only if the first 4 PCs are selected.

All in all, although the repetitive VBS movement can be explained by at least 3 principal components (PCs) for all participant groups, PCA and UCM analyzes of this study conducted based on the first 4 principal components (PCs) for the dominant side, the non-dominant side, and two-leg-together (16 muscles) conditions to keep all data comparable. Each participant of the three groups had at least one significant factor loading (absolute value more than 50% (86) in the 4th PC (see section 4.2 *Composition of Muscle Modes* for detail). Nonetheless, in 5th and higher PCs, there was no significant factor loadings of the muscles for most of the subjects. There was no outlier participant in terms of the number of PCs. In other words, no participant was excluded because of explaining the total variance (> 70%) with different number of muscle modes (PCs) e.g., 2 or 5.

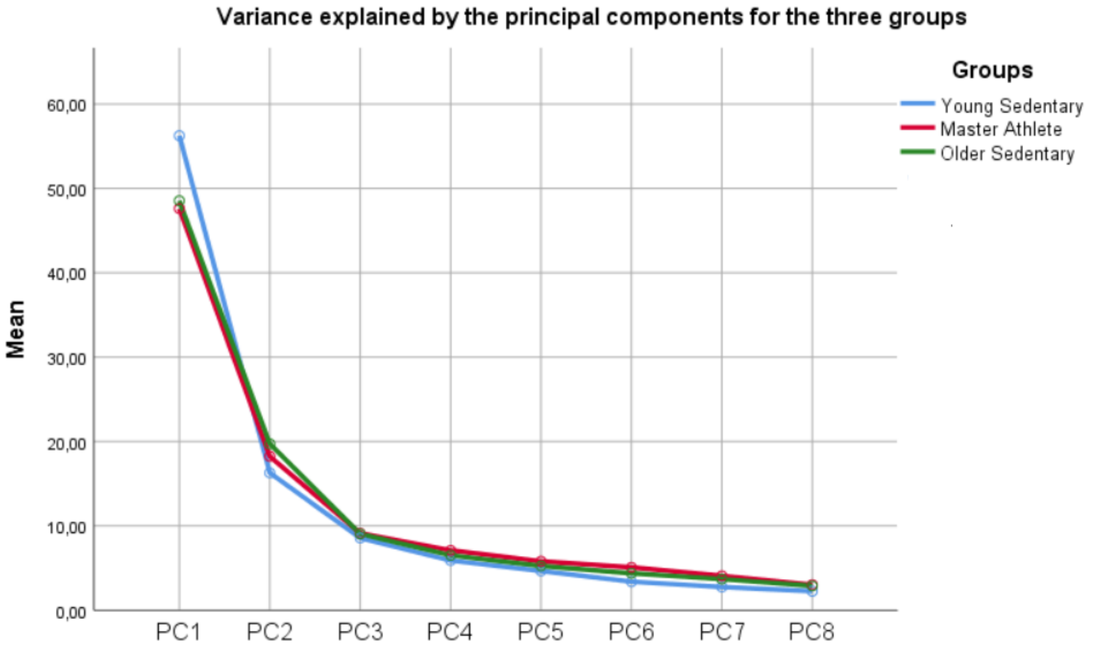


Figure 4.2 Percentage of variance explained by each principal components for the dominant side of the three groups.

Table 4.1 Percentage of variance explained by the first 4 principal components for the dominant side of the three groups.

	Young Sedentary (N=12)	Master Athlete (N=12)	Older Sedentary (N=11)
% Variance explained by the first 4 PCs (M ± SS)	% 87.0 ± 3.9	% 82.1 ± 4.6	% 83.8 ± 4.6

Table 4.1 demonstrates the percentage of variance explained by the first 4 principal components (PC1, PC2, PC3 and PC4) were found above 80% in all groups during repetitive voluntary sway movement. The percentage of variance explained by

the first 4 PCs in the young sedentary group is slightly higher than in the older sedentary group and in the master athletes.

4.2 Composition of Muscle Modes

PCA was applied to 8 dominant lower extremity muscles “TA, RF, VL, VM, GM, SOL, BF, ST” of each subject to determine principal components (i.e., muscle modes) of repetitive VBS motion. The number of PCs i.e., muscle modes was determined as 4 to analyze for the three participant groups. Thus, 4 muscle modes (4 PCs) for each subject and the representation of 8 skeletal muscles in terms of factor loadings in each muscle mode were determined.

Factor Loadings of Muscle Modes

In this section, factor loadings of the muscles in each of the muscle modes (PCs) and muscle mode compositions (reciprocal or co-activation types of muscle mode composition) were examined.

Young sedentary group and master athlete group could be represented by one typical subject in terms of the set of typical factor loadings of each PC, but older sedentary group needed to be represented by two typical subjects. Table 4.2 shows representative sets of factor loadings of each PCs (PC1, PC2, PC3, PC4) for one typical subject of young sedentary and master athlete groups. Table 4.3 shows representative sets of factor loadings of each PCs (PC1, PC2, PC3, PC4) for two typical subjects of older sedentary group. Factor loadings tables of each PC for each participant of the three groups are represented in Appendix 4 for both the first 3 PCs and the first 4 PCs. When the absolute factor loading value of the muscle in each PC was above 50%, i.e., 0.5, the representation of the muscle in the relevant principal component was considered significant (86) and demonstrated highlighted and bold. Positive (+) and negative (-) values represent agonist and antagonist working muscles in the same PC. For each PC, if the agonist muscles are represented +, the antagonists are represented - and vice versa.

Table 4.2 Representative sets of factor loadings of each PC for one typical subject of young sedentary and master athlete groups.

	Young Sedentary				**Master Athlete**			
Muscles	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
TA	**0.92**	-0.18	0.14	-0.08	-0.24	0.19	**0.91**	0.16
SOL	-0.41	0.38	-0.32	**0.76**	**0.88**	-0.21	-0.08	-0.10
GM	-0.30	0.38	**-0.83**	0.26	**0.90**	-0.15	-0.10	-0.05
RF	**0.82**	-0.21	0.23	-0.31	-0.16	0.19	0.13	**0.93**
VL	**0.86**	-0.21	0.19	-0.24	-0.20	**0.56**	0.26	0.43
VM	**0.88**	-0.20	0.21	-0.24	-0.08	**0.93**	0.07	0.11
BF	-0.19	**0.91**	-0.26	0.20	**0.79**	0.01	-0.16	-0.18
ST	**-0.58**	**0.56**	-0.27	0.36	**0.71**	0.00	-0.45	-0.13

Table 4.3 Representative sets of factor loadings of each PC for two typical subjects (named A and B) of older sedentary group.

	Older Sedentary - A				**Older Sedentary - B**			
Muscles	PC1	PC2	PC3	PC4	PC1	PC2	PC3	PC4
TA	-0.08	0.32	**0.94**	0.00	0.18	0.11	**0.95**	-0.01
SOL	**0.60**	-0.03	0.00	**0.76**	-0.44	0.31	0.33	**0.51**
GM	**0.88**	-0.18	-0.01	0.28	-0.18	0.25	-0.07	**0.91**
RF	-0.12	**0.87**	0.10	0.12	**0.87**	-0.08	0.06	-0.16
VL	-0.06	**0.86**	0.16	-0.16	**0.85**	-0.06	0.09	-0.11
VM	-0.20	**0.81**	0.21	-0.03	**0.86**	-0.09	0.09	-0.13
BF	**0.90**	-0.24	-0.14	-0.07	-0.03	**0.93**	0.05	0.15
ST	**0.85**	-0.03	-0.03	0.34	-0.18	**0.88**	0.12	0.22

Table 4.4 Number of total appearances of significantly loaded muscles in each PC for each subject of the three groups.

Young Sedentary					**Master Athlete**					**Older Sedentary**				
Muscles	PC1	PC2	PC3	PC4	Muscles	PC1	PC2	PC3	PC4	Muscles	PC1	PC2	PC3	PC4
TA	**10**		1	2	*TA*	4	1	**5**	3	*TA*	1	1	**6**	**4**
SOL	5	**4**	1	**4**	*SOL*	**9**		1	3	*SOL*	**6**	2	2	3
GM	1	**5**	**3**	2	*GM*	**9**			3	*GM*	**7**	1	1	2
RF	**8**	2	2	2	*RF*	3	**4**	2	2	*RF*	**5**	**4**	1	2
VL	**8**	1		3	*VL*	3	**4**	2	3	*VL*	**5**	**5**		1
VM	**8**	2		1	*VM*	2	**9**		2	*VM*	**5**	**4**	1	1
BF	3	**5**	2	2	*BF*	**6**	3	2	2	*BF*	4	2	**4**	1
ST	4	**3**	**4**	1	*ST*	**9**	1	2		*ST*	3	**4**	2	3

Table 4.4 quantitatively visualizes the number of total appearances of significantly loaded 8 skeletal muscles in each of the 4 PCs for each subject of the

three groups in order to understand factor loadings features of each PC for each one of the subjects of the three groups. Muscles that have the highest numbers of total appearance as significantly loaded in a PC demonstrated highlighted and bold. For example, number *10* for *TA* muscle under the *PC1* of *Young Sedentary* column in Table 4.4 means that 10 subjects showed significant factor loadings for TA muscle in PC1 of young sedentary group.

Table 4.5 Mainly loaded muscle groups in each muscle mode (PC1, PC2, PC3, PC4) of each subject of the three groups; as ventral group (V), dorsal group (D) or ventral-dorsal group together (V-D).

	Young Sedentary				**Master Athlete**				**Older Sedentary**			
#S	*PC1*	*PC2*	*PC3*	*PC4*	*PC1*	*PC2*	*PC3*	*PC4*	*PC1*	*PC2*	*PC3*	*PC4*
1	V	D	D	D	D	V	V	V	V-D	D	D	V
2	V	D	D	D	V	D	V-D	D	D	V	V	D
3	D	V	V	V	D	V	D	V	V	D	V	D
4	V-D	D	D	V	D	V	V	V	V	D	D	V
5	V	D	D	D	D	V-D	V	V	V	D	V	D
6	V	D	V	D	D	V	V	V	D	V	D	V
7	D	V	D	V	D	V	V	V	D	V	V	D
8	V	D	D	D	V	D	V	D	D	D	V	V
9	V	D	D	V-D	D	V	V	D	V	D	D	V
10	V	D	D	V	D	V	D	V	D	V	V	D
11	V	D	D	D	D	V	V	V	D	V	V	V
12	D	V	V	V	V	D	D	D				
∑V	**8**	3	3	5	3	**8**	**8**	**8**	4	5	7	6
∑D	3	**9**	**9**	6	**9**	3	3	4	6	6	4	5
∑V-D	1	-	-	1	-	1	1	-	1	-	-	-

Ventral group includes some or all of TA, RF, VL, VM muscles and dorsal group includes some or all of SOL, GM, BF, ST muscles and ventral-dorsal group includes muscles of both ventral group and dorsal group. The first column represents the number of subjects and the last three rows of the first column represents total number of V, D and V-D seen in each PC for the relevant group.

In order to understand the anatomical functions of significantly loaded muscles in each PC for each subject of the three groups, Table 4.5 demonstrates mainly loaded muscle groups in each muscle mode (PC1, PC2, PC3, PC4) of each subject in the three groups; as ventral group (V), dorsal group (D) or ventral-dorsal group together (V-D). For this study, ventral group (V) includes some or all of TA, RF, VL, VM muscles and dorsal group (D) includes some or all of SOL, GM, BF, ST muscles and ventral-dorsal group together (V-D) includes muscles of both ventral group and dorsal group. Total number of V, D and V-D seen in each PC presented in the last three rows of the Table 4.5. If there was a predominance in terms of the total number of mainly loaded muscle group (V, D or V-D) in the PCs that are demonstrated highlighted and bold. For example, *V* for *#S1* under the *PC1* of *Young Sedentary* column in Table 4.5 means that significant factor loadings mainly belonged to ventral muscle group in PC1 of young sedentary group.

In the young sedentary group, there was a trend in the predominant use of ventral or dorsal muscles in the muscle modes (PCs). Young sedentary group mainly used ventral muscle group (TA, RF, VL, VM) in PC1, dorsal muscle group (SOL, GM, BF, ST) in PC2 and dorsal muscles (GM, ST) in PC3 which are shown in Table 4.4. Moreover, Table 4.5 demonstrates mainly loaded muscles groups in each muscle mode for each subject of young sedentary group. In PC1, 8 people mainly used the ventral muscles, 3 people mainly used the dorsal muscles, and 1 person used the ventral and dorsal muscles together in the young sedentary group. In PC2 and PC3, 3 people mainly used the ventral muscles, 9 people mainly used the dorsal muscles. In PC4, 5 people mainly used the ventral muscles, 6 people mainly used the dorsal muscles, and 1 person used the ventral and dorsal muscles together.

In the master athlete group, there was a trend in the predominant use of ventral or dorsal muscles in the muscle modes (PCs). Master athletes mainly used dorsal muscles (SOL, GM, BF, ST) in PC1 and ventral muscles in PC2 (RF, VL, VM) and PC3 (TA) which is shown in Table 4.4. Furthermore, Table 4.5 demonstrates mainly used muscles groups in each muscle mode for each subject of master athletes. In PC1, 3 people mainly used the ventral muscles, 9 people mainly used the dorsal muscles. In PC2 and PC3, 8 people mainly used the ventral muscles, 3 people mainly used the dorsal muscles, and 1 person used the ventral and dorsal muscles together. In PC4, 8 people mainly used the ventral muscles, 4 people mainly used the dorsal muscles.

In the older sedentary group, there was no apparent trend in the predominant use of ventral or dorsal muscle groups in the muscle modes (PCs) as shown in Table 4.4. According to Table 4.5, in PC1, 4 people mainly used the ventral muscles, and 6 people mainly used the dorsal muscles, and 1 person used the ventral and dorsal muscles together. In PC2, 5 people mainly used the ventral muscles, and 6 people mainly used the dorsal muscles. In PC3, 7 people mainly used the ventral muscles, 4 people mainly used the dorsal muscle. In PC4, 6 people mainly used the ventral muscles, 5 people mainly used the dorsal muscle.

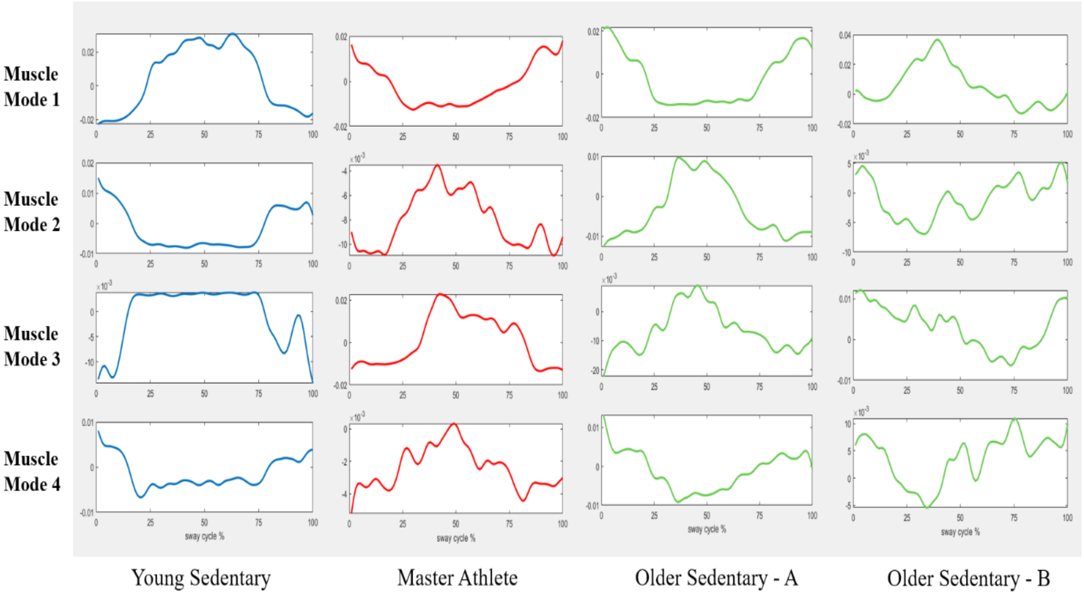


Figure 4.3 Magnitude-time change plots of 4 muscle modes (4 PCs) over time during a sway cycle of voluntary body sway motion for the three groups.

Figure 4.3 demonstrates the representative magnitude-time change plots of 4 muscle modes (4 PCs) over time during a sway cycle of voluntary body sway motion for the three groups. Representative subjects demonstrated in Figure 4.3 are the same with the representative subjects of Table 4.2 and Table 4.3. Compatible with Table 4.4 and Table 4.5, it is seen in Figure 4.3 that young sedentary group used ventral muscle group in muscle mode 1 (activation increase in the posterior phases) and dorsal group in muscle mode 2 (activation increases in the anterior phases), (see Figure 3.5 for sway cycle phases). Master athlete group used dorsal muscle group in muscle mode 1 (activation increases in the anterior phases) and ventral muscle group in muscle mode 2 (activation increases in the posterior phases). Moreover, muscle mode magnitude-time profile of older sedentary group is represented with two typical subjects because there was no apparent trend in the predominant use of ventral or dorsal muscle groups in the muscle modes (PCs) as compatible with Table 4.5.

Mean Sway Range

Mean sway range in AP direction (in cm) is calculated for each subject of the three groups. Considering the height of subject's body center of mass is a factor that potentially influences the sway range, mean sway range (in cm) values are divided to the subject's body height (in cm) and a unitless ratio is handled for each subject. This unitless ratio of mean sway range to the subject's body height are more comparable among subjects since the height of subject's body center of mass factor is tried to eliminate by this normalization (dividing by body height).

Table 4.6 Mean sway range in AP direction (in cm) and the ratio of mean sway range to the subject's body height (cm/cm: unitless) of the three groups.

	Young Sedentary (N=12)	Master Athlete (N=12)	Older Sedentary (N=11)	Statistical significance
mean sway range [cm] (M ± SS)	15.1 cm ± 1.7	13.2 cm ± 2.1	12.4 cm ± 2.5	YS>OS
mean sway range over height ratio [unitless] (M ± SS)	0.087 ± 0.009	0.076 ± 0.011	0.072 ± 0.012	YS>MA, YS>OS

YS is young sedentary group, MA is master athletes and OS is older sedentary group. Statistical significance column shows cases where group differences are significant (p<.05) as a result of ANOVA.

Mean sway ranges in AP direction and the ratios of mean sway range to the subject's body height of the three groups are demonstrated in Table 4.6. Tukey HSD post hoc test revealed that mean sway range was higher in young sedentary group than in older sedentary group, $p<.05$, 95% *C.I.*=[.5757-4.8987]. There was no statistically significant difference between master athletes and sedentary groups (young and older), $p>.05$. The mean sway range over height ratio is found significantly higher in young sedentary group in comparison with master athletes ($p<.05$, 95% *C.I.*=[.0001-.0222]) and older sedentary group ($p<.01$, 95% *C.I.*=[.0037-.0263]) as a result of Tukey HSD post hoc test.

Reciprocal or Co-Activation Contraction Pattern

Depending on the stimulation of the agonist or antagonist muscles in the muscle mode, the muscle mode may exhibit a *reciprocal* or *co-activation* contraction pattern, that is, the composition of muscle mode. In the *reciprocal* contraction pattern, the agonist muscles are activated while the antagonist muscles are inhibited. In the *co-*

activation contraction pattern, the agonist and antagonist muscles are activated together.

Four muscle modes (PC1, PC2, PC3, PC4) of each subject were examined in order to determine their muscle mode composition, i.e., reciprocal or co-activation contraction pattern, based on the criteria defined in section 3.4.4 *Determination of Muscle Mode Composition*. Table 4.7 demonstrates the number of subjects in each group who has co-activation pattern and reciprocal pattern as the muscle mode composition. The number of subjects in each group who has co-activation muscle mode in at least one PC was given in "*Co-activation muscle mode*" row. The number of subjects in each group who has reciprocal muscle mode in all of the 4 PCs was given in "*Reciprocal muscle mode*" row. As seen in Table 4.7, almost all participants of the three groups had reciprocal muscle mode during voluntary sway motion. Only one participant from master athlete group had co-activation muscle mode which was only on one PC (PC2) and it was knee co-activation type.

Table 4.7 The number of subjects in each group who has co-activation pattern and reciprocal pattern as the muscle mode composition.

	Young Sedentary (N=12)	Master Athlete (N=12)	Older Sedentary (N=11)
Co-activation muscle mode	0	1	0
Reciprocal muscle mode	12	11	11

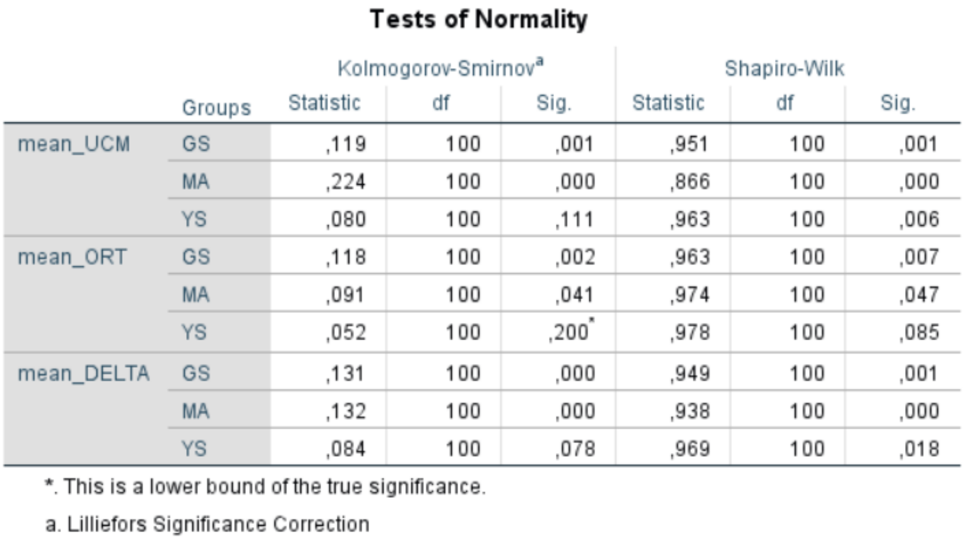
4.3 Variance Components (V_{UCM} and V_{ORT}) and Synergy Index (ΔV)

The variance components (V_{UCM} and V_{ORT}) and synergy index (ΔV), which were created by motor control system by the arrangement of the elementary variables (muscle modes) to stabilize the performance parameter (M_Y) during voluntary sway motion, were determined by the Uncontrolled Manifold, UCM analysis (2) by Matlab program for dominant muscles of each participant the three groups.

V_{UCM}, V_{ORT} and ΔV (synergy index) dependent variables subjected to Shapiro-Wilk test to assess normal distribution and to Levene's test to assess variance homogeneity between dependent variables in order to decide whether these dependent variables satisfy parametric assumptions or not. As seen in the Table 4.8, based on

Shapiro-Wilk test V_{UCM}, ΔV variables seem to deviate from normal distribution for all groups and V_{ORT} seems to deviate from normal distribution for young sedentary group and master athlete group, *p*>.05. Therefore, V_{UCM}, V_{ORT} and ΔV (synergy index) variables did not satisfy normality assumption. Levene's test statistics are shown in Table 4.9. V_{UCM}, V_{ORT} and ΔV (synergy index) dependent variables seem to have significantly different variances, *p*=.00. So, dependent variables did not satisfy homogeneity of variance. In other words, V_{UCM}, V_{ORT} and ΔV (synergy index) dependent variables did not satisfy parametric assumptions.

Table 4.8 Normality test statistics of V_{UCM}, V_{ORT} and ΔV of the three groups.



Tests of Normality

		Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Groups	Statistic	df	Sig.	Statistic	df	Sig.
mean_UCM	GS	,119	100	,001	,951	100	,001
	MA	,224	100	,000	,866	100	,000
	YS	,080	100	,111	,963	100	,006
mean_ORT	GS	,118	100	,002	,963	100	,007
	MA	,091	100	,041	,974	100	,047
	YS	,052	100	,200*	,978	100	,085
mean_DELTA	GS	,131	100	,000	,949	100	,001
	MA	,132	100	,000	,938	100	,000
	YS	,084	100	,078	,969	100	,018

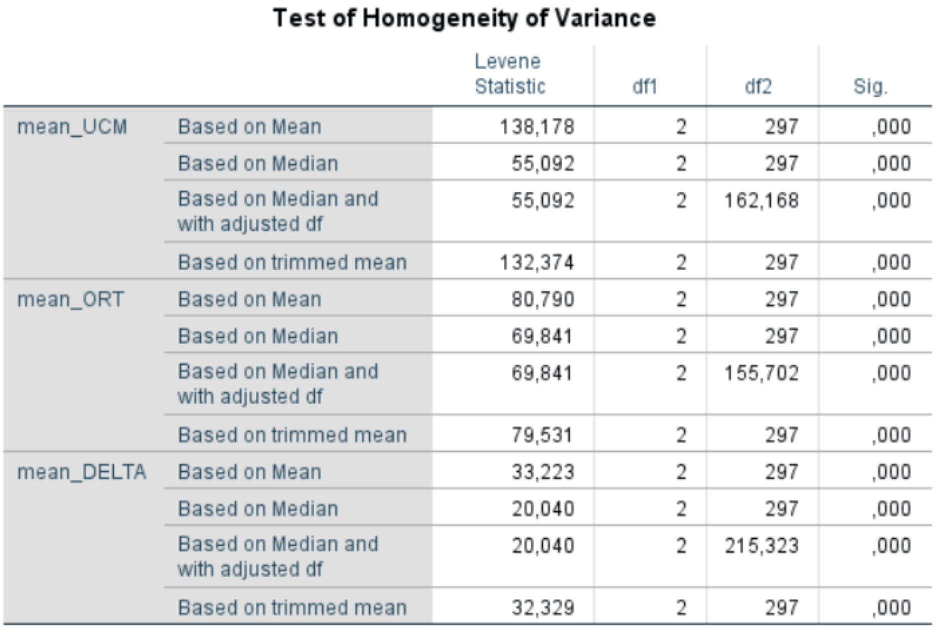
*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

Therefore, between-group comparisons for V_{UCM}, V_{ORT} and ΔV conducted by a non-parametric method, Kruskal-Wallis test. Kruskal-Wallis test statistics are shown in Table 4.10. V_{UCM}, *H*(2)=199.93, *p*=.00, V_{ORT}, *H*(2)=258.37, *p*=.00, and ΔV, *H*(2)=35.85, *p*=.00, dependent variables were significantly different among three groups.

Further statistical analysis conducted with Mann-Whitney test as a Post hoc analysis. Table 4.11, Table 4.12 and Table 4.13 demonstrates between-group comparisons with Mann-Whitney test statistics of V_{UCM}, V_{ORT} and ΔV for dominant muscles. Table 4.14 shows median values of V_{UCM}, V_{ORT} and ΔV for dominant muscles of the three groups.

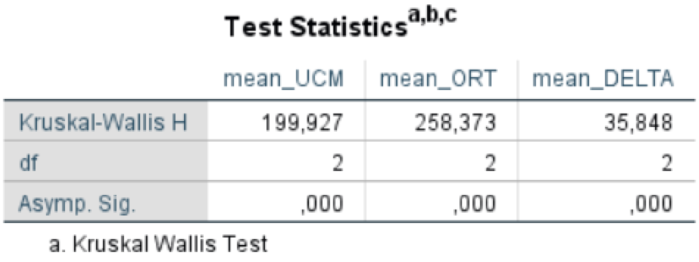
Table 4.9 Homogeneity of variance test statistics of V_{UCM}, V_{ORT} and ΔV.



Test of Homogeneity of Variance

		Levene Statistic	df1	df2	Sig.
mean_UCM	Based on Mean	138,178	2	297	,000
	Based on Median	55,092	2	297	,000
	Based on Median and with adjusted df	55,092	2	162,168	,000
	Based on trimmed mean	132,374	2	297	,000
mean_ORT	Based on Mean	80,790	2	297	,000
	Based on Median	69,841	2	297	,000
	Based on Median and with adjusted df	69,841	2	155,702	,000
	Based on trimmed mean	79,531	2	297	,000
mean_DELTA	Based on Mean	33,223	2	297	,000
	Based on Median	20,040	2	297	,000
	Based on Median and with adjusted df	20,040	2	215,323	,000
	Based on trimmed mean	32,329	2	297	,000

Table 4.10 Kruskal-Wallis test statistics of V_{UCM}, V_{ORT} and ΔV.

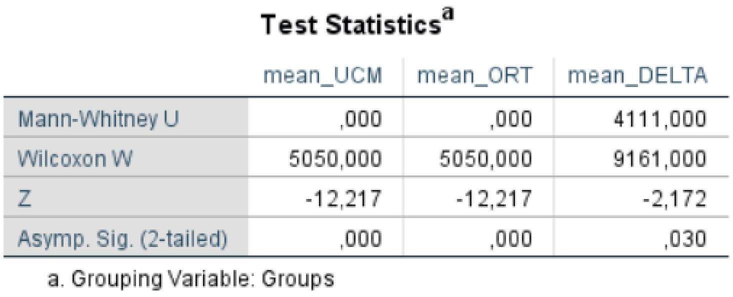


Test Statistics[a,b,c]

	mean_UCM	mean_ORT	mean_DELTA
Kruskal-Wallis H	199,927	258,373	35,848
df	2	2	2
Asymp. Sig.	,000	,000	,000

a. Kruskal Wallis Test

Table 4.11 Mann-Whitney test statistics of V_{UCM}, V_{ORT} and ΔV of young sedentary and master athlete groups.

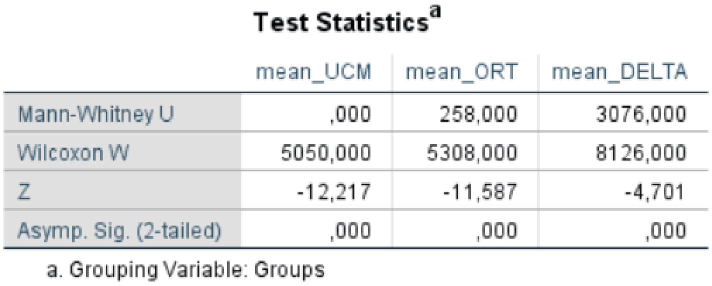


Test Statistics[a]

	mean_UCM	mean_ORT	mean_DELTA
Mann-Whitney U	,000	,000	4111,000
Wilcoxon W	5050,000	5050,000	9161,000
Z	-12,217	-12,217	-2,172
Asymp. Sig. (2-tailed)	,000	,000	,030

a. Grouping Variable: Groups

Table 4.12 Mann-Whitney test statistics of V_{UCM}, V_{ORT} and ΔV of young sedentary and older sedentary groups.

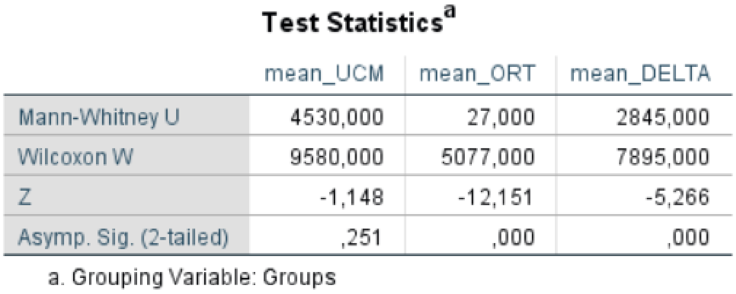


Test Statistics[a]

	mean_UCM	mean_ORT	mean_DELTA
Mann-Whitney U	,000	258,000	3076,000
Wilcoxon W	5050,000	5308,000	8126,000
Z	-12,217	-11,587	-4,701
Asymp. Sig. (2-tailed)	,000	,000	,000

a. Grouping Variable: Groups

Table 4.13 Mann-Whitney test statistics of V_{UCM}, V_{ORT} and ΔV of master athlete and older sedentary groups.



Test Statistics[a]

	mean_UCM	mean_ORT	mean_DELTA
Mann-Whitney U	4530,000	27,000	2845,000
Wilcoxon W	9580,000	5077,000	7895,000
Z	-1,148	-12,151	-5,266
Asymp. Sig. (2-tailed)	,251	,000	,000

a. Grouping Variable: Groups

Table 4.14 Median values of V_{UCM}, V_{ORT} and ΔV of the three groups.

	Young Sedentary (N=12)	Master Athlete (N=12)	Older Sedentary (N=11)
Median V_{UCM}	.000024	.000060	.000073
Median V_{ORT}	.000015	.000051	.000027
Median ΔV	.3218	.1326	.3986

The findings and graphs of variance components and synergy index are presented below under the specific titles.

Figure 4.5 and Figure 4.7 demonstrates below the bar graphs of the between group comparisons of V_{UCM}, V_{ORT} and ΔV (synergy index). The patterns of V_{UCM}, V_{ORT} and ΔV (synergy index) should also be investigated based on the phases of voluntary sway cycles for each group (see Figure 3.5 for the demonstration of a time normalized (0-100%) sway cycle and the phases of a sway cycle). Figure 4.4, Figure 4.6 and Figure 4.7 shows below the patterns of V_{UCM}, V_{ORT} and ΔV (synergy index) during the phases of a sway cycle for each group.

4.3.1 Variance Within the UCM (V_{UCM})

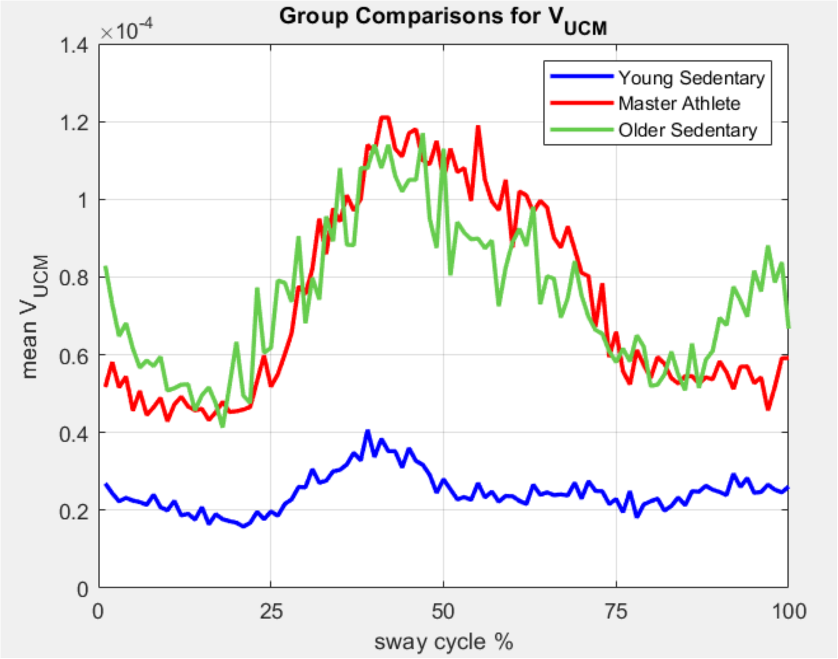


Figure 4.4 Line graph for the values of mean V_{UCM} of the three groups during the sway cycle.

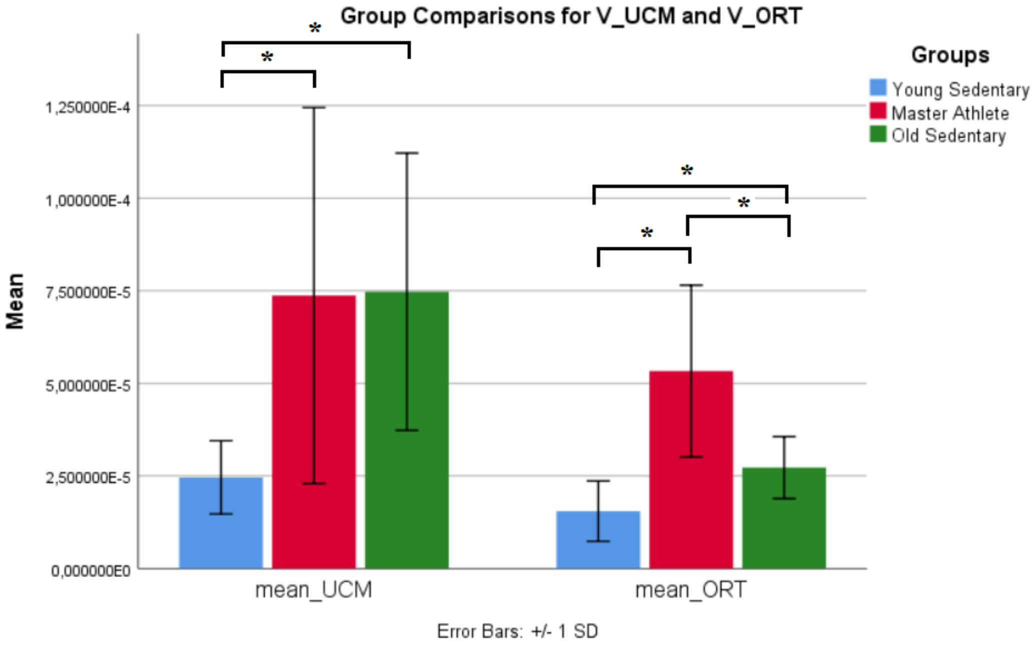


Figure 4.5 Bar graph for the values of mean V_{UCM} and V_{ORT} of the three groups. “*” mark indicates statistically significant difference between the indicated groups.

Figure 4.4 shows the line graph for the values of mean V_{UCM} of the three groups during the sway cycle. Moreover, Figure 4.5 shows the bar graph for the values of mean V_{UCM} and V_{ORT} of the three groups.

Between group comparisons of V_{UCM}:

- Master athletes (*Mdn*=.000060) had significantly higher V_{UCM} value than young sedentary group (*Mdn*=.000024), *U*=.00, *z*=-12.22, *p*=.00.
- Older sedentary group (*Mdn*=.000073) had significantly higher V_{UCM} value than young sedentary group (*Mdn*=.000024), *U*=.00, *z*=-12.22, *p*=.00.
- There was no significant difference between V_{UCM} values of master athletes (*Mdn*=.000060) and older sedentary group (*Mdn*=.000073), *p*>.05.

4.3.2 Variance Orthogonal to the UCM (V_{ORT})

Figure 4.6 shows the line graph for the values of mean V_{ORT} of the three groups during the sway cycle.

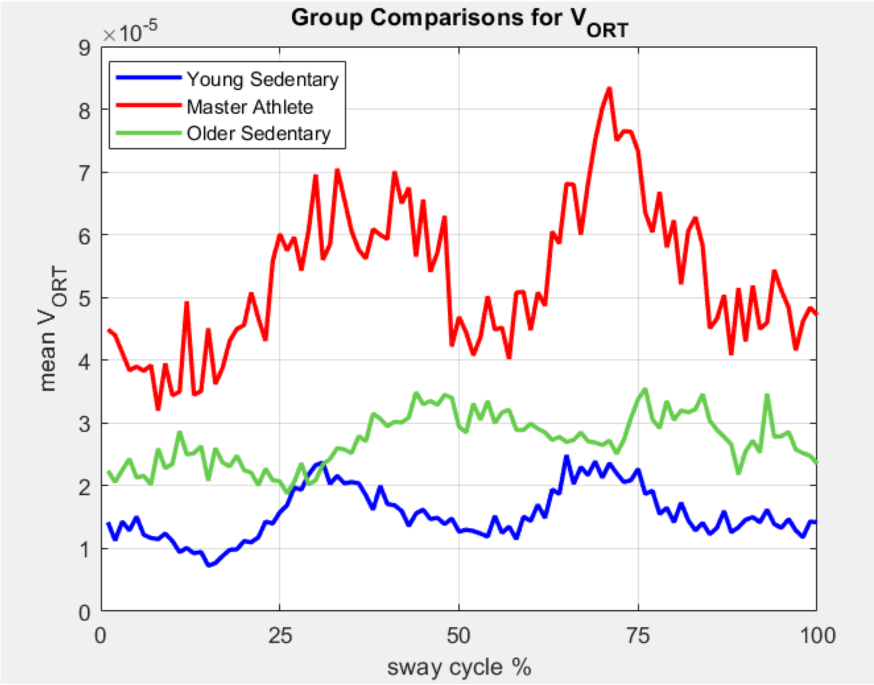


Figure 4.6 Line graph for the values of mean V_{ORT} of the three groups during the sway cycle.

Between group comparisons of V_{ORT}:

- Master athletes (*Mdn*=.000051) had significantly higher V_{ORT} value than older sedentary group (*Mdn*=.000027), *U*=27.00, *z*=-12.15, *p*=.00, and young sedentary group (*Mdn*=.000015), *U*=.00, *z*=-12.22, *p*=.00.
- Older sedentary group (*Mdn*=.000027) had significantly higher V_{ORT} value than young sedentary group (*Mdn*=.000015), *U*=258.00, *z*=-11.59, *p*=.00.

4.3.3 Synergy Index (ΔV)

Figure 4.7 shows the line graph for the values of mean ΔV (synergy index) of the three groups during the sway cycle. Figure 4.8 shows the bar graph for the values of mean ΔV (synergy index) of the three groups.

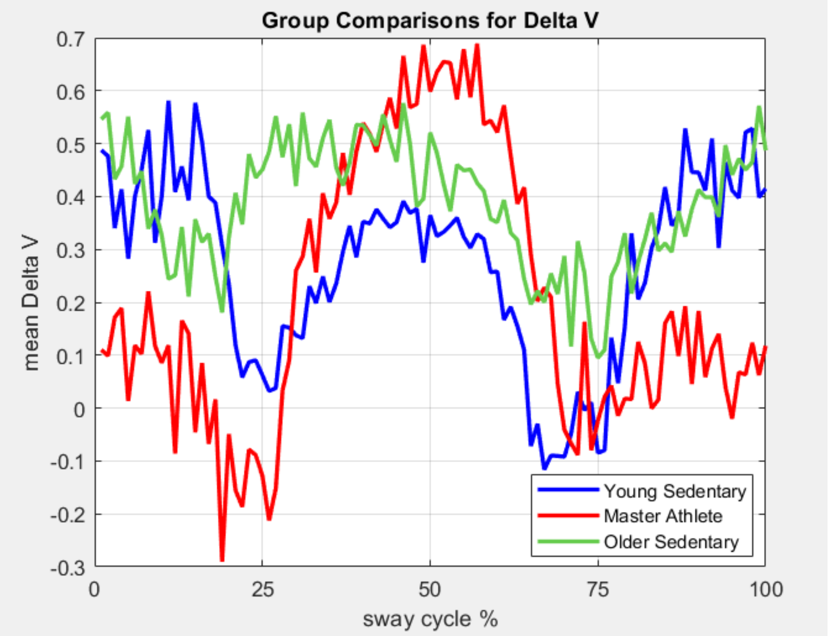


Figure 4.7 Line graph for the values of mean ΔV of the three groups during the sway cycle.

Between group comparisons of ΔV:

- Older sedentary group (*Mdn*=.3986) had significantly higher Delta V value than young sedentary group (*Mdn*=.3218), *U*=3076.00, *z*=-4.70, *p*=.00, and master athletes (*Mdn*=.1326), *U*=2845.00, *z*=-5.27, *p*=.00.
- Young sedentary group (*Mdn*=.3218) had significantly higher Delta V value than master athletes (*Mdn*=.1326) *U*=4111.00, *z*=-2.17, *p*<.05.

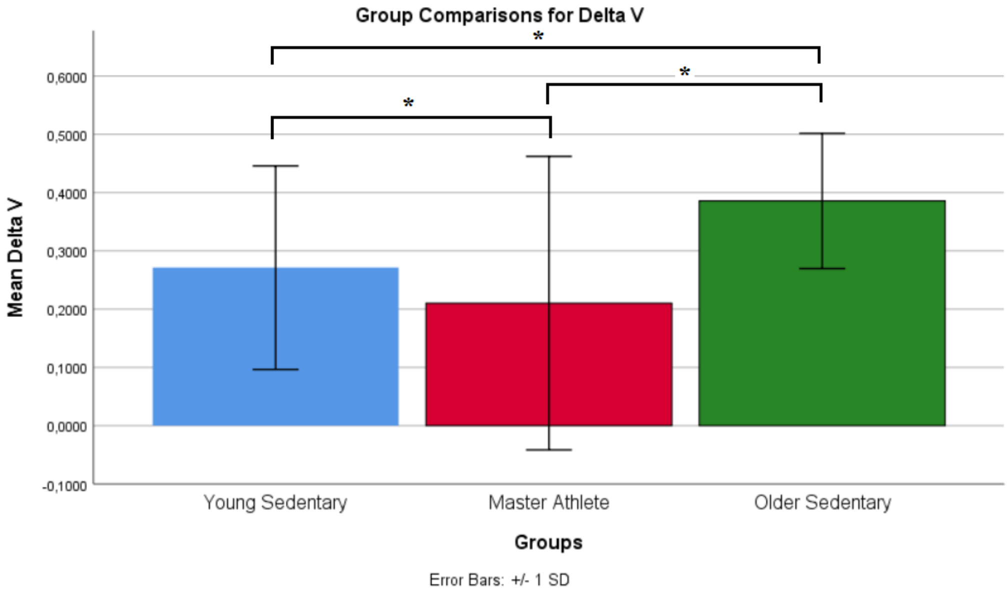


Figure 4.8 Bar graph for the values of mean ΔV (synergy index) of the three groups. “*” mark indicates statistically significant difference between the indicated groups.

4.4. Effect of Lower Limb Laterality on Muscle Synergies

In this part of the study, the muscle synergy analyzes made so far were repeated for non-dominant side of the lower extremity (on 8 muscles) and two-legs-together (16 muscles) conditions to compare the results of muscle synergy analysis (variance components and synergy index) among three conditions: the dominant side (8 muscles), the non-dominant side (8 muscles) and two-legs-together (16 muscles), (see section 3.4.6 *Lower Limb Laterality on Muscle Synergies* for detail).

PCA results of the dominant (8 muscles), non-dominant (8 muscles) and two-legs-together (16 muscles) conditions are presented in Appendix 5 including the tables of percentage of variance explained, number of total appearances of the significantly loaded muscles, mainly used muscles groups in each muscle mode.

Figure 4.9, Figure 4.10, Figure 4.11 show below the bar graphs and the line graphs for the values of mean V_{UCM}, V_{ORT}, ΔV (synergy index) of the three groups during the sway cycle for three conditions to compare: dominant 8 muscles, non-dominant 8 muscles and two-legs-together 16 muscles.

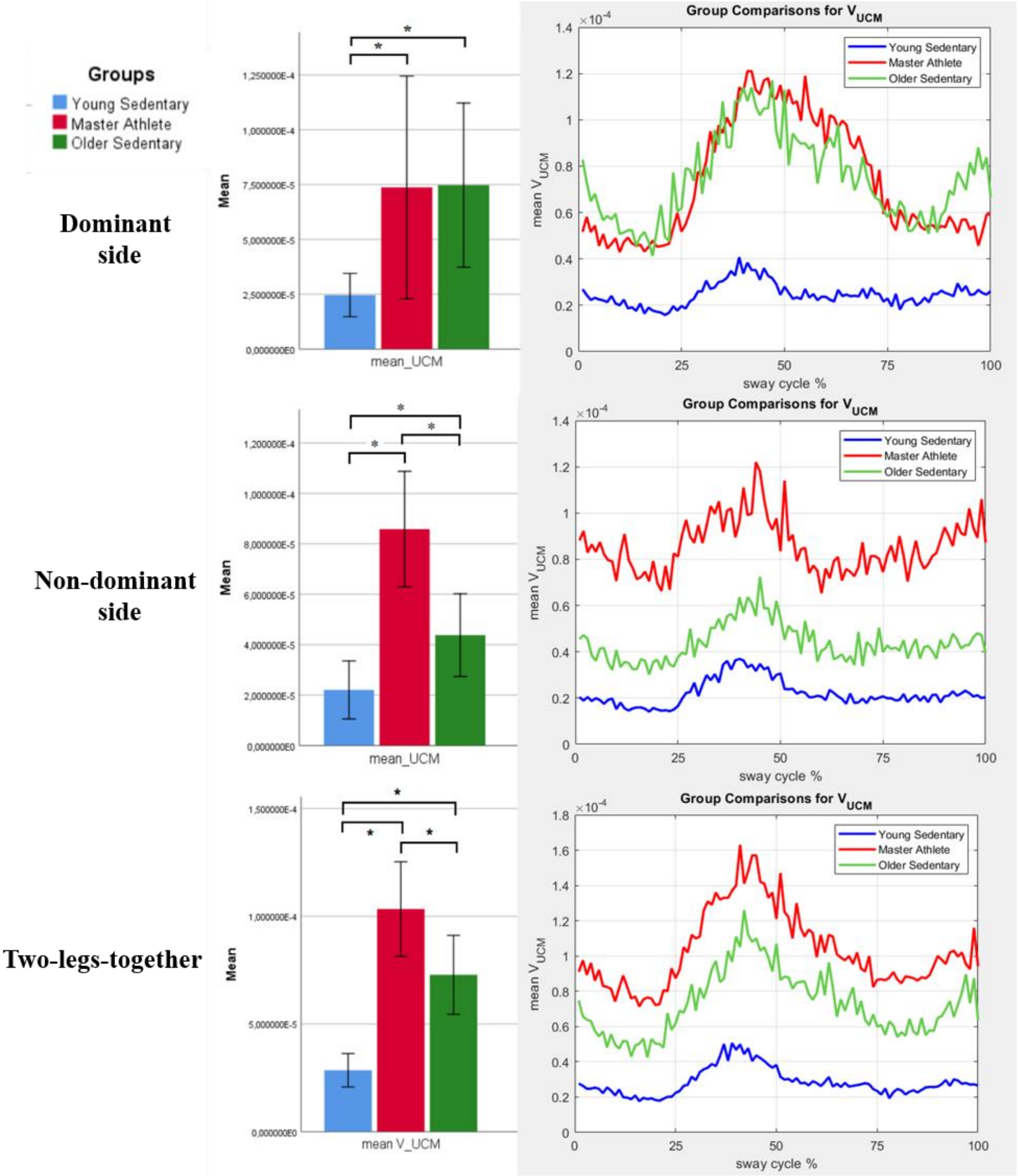


Figure 4.9 Bar graph and line graph for the values of mean V_{UCM} of the three groups during the sway cycle for dominant 8 muscles, non-dominant 8 muscles and two-legs-together 16 muscles. “*” mark indicates statistically significant difference between the indicated groups.

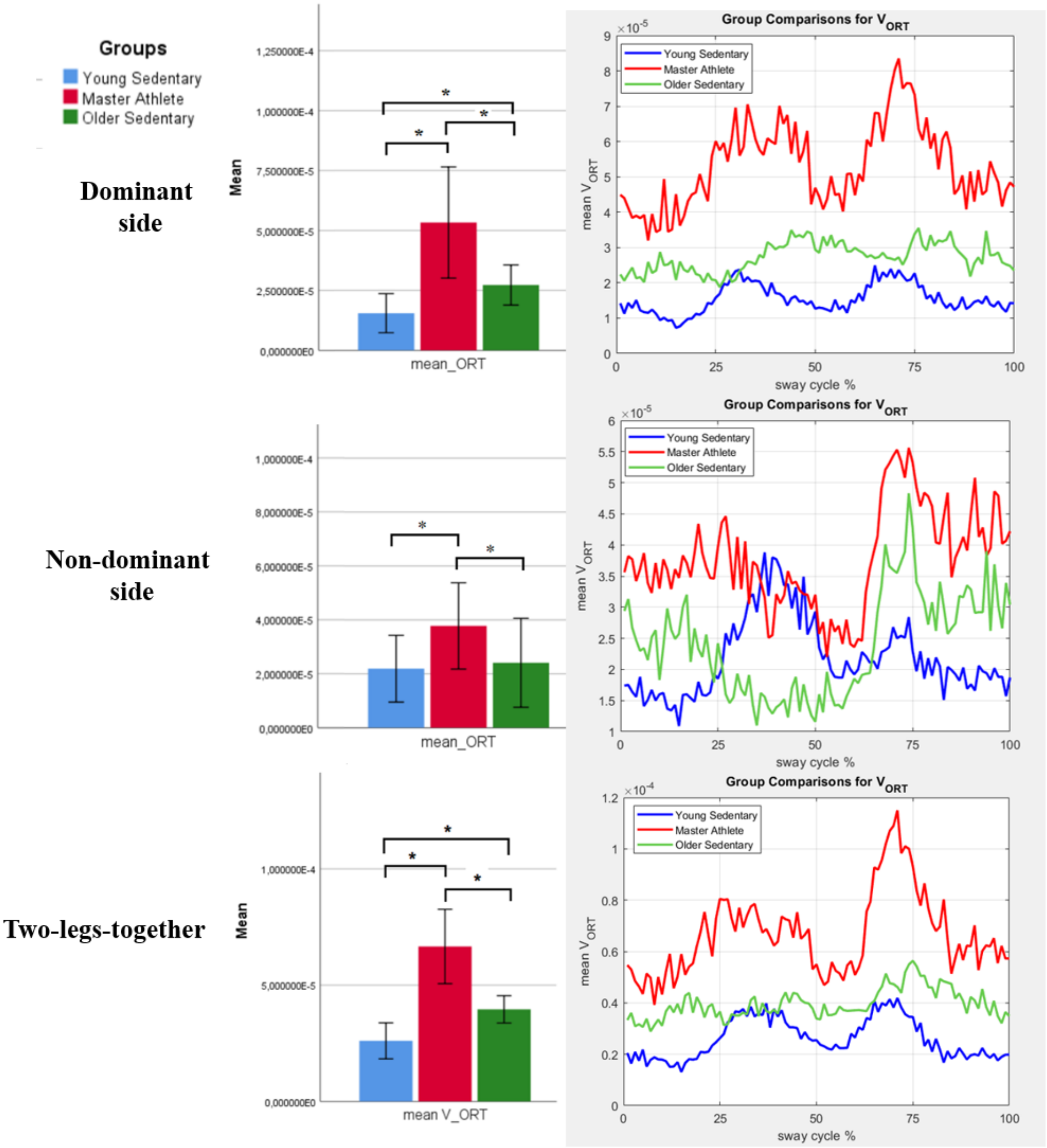


Figure 4.10 Bar graph and line graph for the values of mean V_{ORT} of the three groups during the sway cycle for dominant 8 muscles, non-dominant 8 muscles and two-legs-together 16 muscles. “*” mark indicates statistically significant difference between the indicated groups.

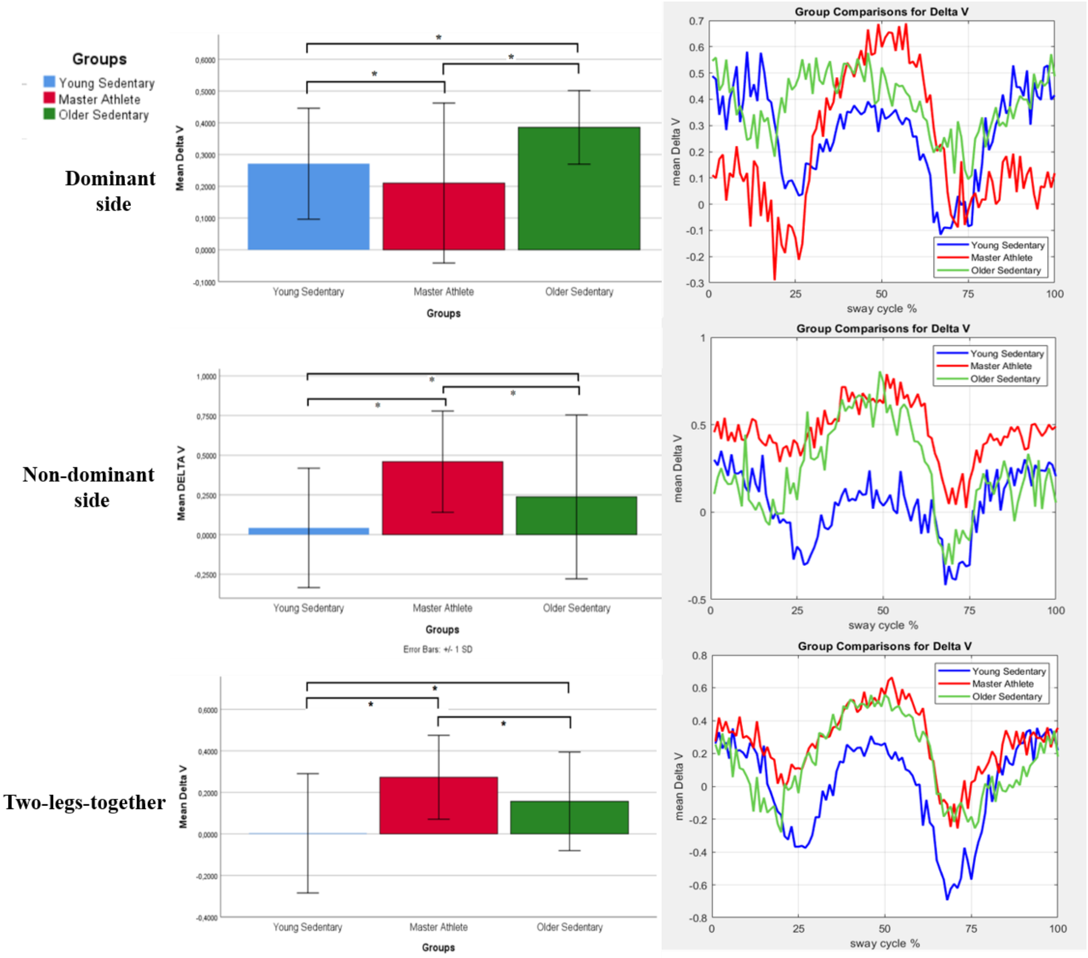


Figure 4.11 Bar graph and line graph for the values of mean ΔV (synergy index) of the three groups during the sway cycle for dominant 8 muscles, non-dominant 8 muscles and two-legs-together 16 muscles. “*” mark indicates statistically significant difference between the indicated groups.

5. DISCUSSION

In this chapter, the findings are discussed with the current knowledge in the literature. The discussions are presented in line with and in order with the hypotheses and research questions of the thesis that are included under the section 1.4 *Hypotheses and Research Questions*.

Figure 4.1 shows that each typical subject of the three groups represented similar and expected muscular activity during one sway cycle of VBS such that the activity of ventral muscles (TA, RF, VL, VM) increased in the posterior phase and the activity of dorsal muscles (GM, SOL, BF, ST) increased in the anterior phases (see Figure 3.5 for sway cycle phases). This was interpreted as the participants followed the experimental protocol correctly and the measurement was taken correctly.

5.1 Number of Muscle Modes

The repetitive VBS movement could be explained by at least 3 principal components (PCs) i.e., 3 muscle modes for all participant groups.

We hypothesized that the number of muscle modes may be higher in the young sedentary group than in the older sedentary group with regard to the idea of age-dependent declined motor flexibility and small motor repertoire in older adults. An and the others' study (8) reported that the number of muscle modes used during sit-to-stand movement was three for young people and varied between one to three for older individuals. The reasons why An and the others found different number of muscle modes between old and young group could be the fact that the mean age of older group in their study (67.1 years of age) was higher than our groups' (62.6 years of age) or the fact that sit-to-stand movement is more complicated movement than voluntary sway task in terms of being multi-joint motion and requiring more muscle power to achieve the transfer of the body center of mass in both sagittal plane and transverse plane. So, the possible limitations in motor flexibility due to advanced age could be visible in their study because of the higher age group or relatively hard task to achieve for the elderly. Our results were compatible with the previous studies examining the relationship between aging and muscle modes such that healthy young and older adults use the same number of muscle modes during the movements such as stepping to different step heights (126), voluntary body sway (127), sit-to-stand (119, 128).

In our second hypothesis, we claimed that the number of muscle modes may be higher in the master runners than in the older sedentary group with regard to the idea of the possible positive effect of regular exercise in the elderly on motor flexibility. Sawers and the others' study (9) showed that young ballerinas used higher number of muscle modes than the sedentary group during walking on a narrow balance board although both groups showed similar movement kinematics. However, in Sawers and the others' study, two groups consist of young adults. In this hypothesis we wanted to compare older groups in different physical activity levels. In the study of Wang and others (14), one of the rare studies examining aging and muscle modes, it was reported that two groups consisting healthy older adults (one group has been regularly dancing and the other group has been regularly walking for a long time) used the same number of muscle modes during preparation for stepping in response to support surface translation. So, our result was compatible with Wang and others study, although their control group was not sedentary but regular walker.

So, the two hypotheses were disproved. It was seen that during voluntary sway movement the number of muscle modes used were the same for older and younger sedentary groups and master athletes. The effect of age and the effect of regular long-term exercise in the elderly were not effective on the number of muscle modes used (motor flexibility) during VBS.

5.2 Composition of Muscle Modes

Factor Loadings of Muscle Modes

During the repetitive VBS movement, young sedentary group used ventral muscle group in muscle mode 1 and dorsal group in muscle mode 2. Master athlete group used dorsal muscle group in muscle mode 1 and ventral muscle group in muscle mode 2. However, there was no apparent trend in the predominant use of ventral or dorsal muscle groups in the muscle modes of older sedentary group. Muscle mode composition differences between the groups are attempted to be interpreted below.

It is known that aging affects the perception of stability limits which might not allow elderly subjects to lean backward as far as young subjects. In older groups as a consequence of narrow posterior boundary of sway, anterior sway might be the most weighted part of the sway cycle in terms of multi-muscular control requirement. However, posterior sway might be the most weighted part of the sway cycle in terms of multi-muscular control requirement the young group since they can lean backward with more freedom and ability to control. If older groups have narrow posterior boundary of sway and multi-muscular control priority to anterior sway during the sway cycle, it would be expected that dorsal muscles are loaded in muscle mode 1 (i.e., in the first PC that explains the most of the variance) as they are responsible for deceleration of anterior phase of the sway.

It might also be a mechanism to compensate ankle muscle weakness observed in the elderly (157, 158), such that they might limit to sway backward and might have recruited dorsal distal and proximal muscles simultaneously.

The collected data was not available to calculate the amount of posterior lean during voluntary sway; however, to give an idea about the hypothesis mentioned above about "*…narrow posterior boundary of sway and multi-muscular control priority to anterior sway during the sway cycle in the elderly…*", mean sway range in AP direction (in cm) and mean sway range over height (i.e., stature of the subject) ratio [unitless] were calculated for each subject of the three groups (see Table 4.6). It was shown that mean sway range in AP direction was significantly larger in young sedentary group in comparison with older sedentary group, where mean sway range over height ratio was significantly larger in young sedentary group in comparison with older sedentary and master athlete groups. The fact that the young people did the VBS movement in a larger range may mean that the older groups may have restricted their posterior lean; however, it is certain that further investigation is needed.

Reciprocal or Co-Activation Contraction Pattern

The co-activation contraction pattern is seen more common in unstable conditions (139, 140), in people with neurological (141) or motor impairments (85, 123, 124, 142) and in older adults (10, 11, 12). It has been shown that the composition of the muscle mode is reorganized and the co-activation pattern turned into a reciprocal pattern as a result of the practice of the given motor task (139) and regular exercise (9, 13, 14).

In the light of this information, we hypothesized that older sedentary group may have higher co-activation level in muscle mode composition than in younger sedentary group (12) and in master athletes (13, 14). In the study of Wang and others (12), it was reported that during voluntary body sway movement, older adults had more co-activation composition, while all young people exhibited a reciprocal composition in their muscle modes. In another study of Wang and the others (14) involving healthy older adults, it has been reported that the dancer group who has been dancing for the last five years used more reciprocal muscle mode pattern and less co-activation pattern in comparison with the non-dancer, regular walker group during preparation for stepping in response to support surface translation.

However, our hypotheses are disproved. As seen in Table 4.7, almost all participants of the three groups had reciprocal pattern during voluntary sway motion. Therefore, in terms of muscle mode composition (reciprocal or co-activation contraction pattern), it was not seen a difference for the participant groups including different age groups and physical activity levels. Based on the previous reports that claim the co-activation contraction pattern is seen more common in unstable conditions (139, 140), in people with neurological (141) or motor impairments (85, 123, 124, 142), we may interpret that this was kind of a prove that our older participants are neurologically healthy enough to not show a co- activation pattern during VBS movement. In addition, VBS movement may not be a challenging task for the older groups to reveal possible muscle mode composition differences between young and older or active and inactive groups.

5.3 Variance Components (V_{UCM} and V_{ORT}) and Synergy Index (ΔV)

The discussions of the findings and graphs of variance components and synergy index are presented below under the specific titles.

5.3.1 Variance Within the UCM (V_{UCM})

The pattern of V_{UCM} was demonstrated during the phases of the sway cycle (see Figure 3.5 for the phases of the sway cycle) for each group in Figure 4.4. For all groups, V_{UCM} value increases around the posterior peak (posterior-to-anterior return) of the motion. This part of the motion includes posterior-to-anterior return which we expect subjects to have difficulty during this return. Since V_{UCM} value increases around the posterior peak of the motion for all groups, all groups have higher V_{UCM} values in posterior phase than anterior phases. Furthermore, V_{UCM} value of older sedentary group increases around the anterior peaks (anterior-to-posterior returns) of the motion. While all subjects increase their good variance (V_{UCM}) during the posterior-to-anterior return part that is the difficult part of the motion, older sedentary group also increase their good variance (V_{UCM}) during anterior-to-posterior returns. This may mean that older sedentary group had difficulties in the anterior peaks, as well.

Master athletes and older sedentary group had similar values of V_{UCM} which were significantly higher than V_{UCM} value of young sedentary group (Figure 4.5). In the study of Wu et al. (159), the older subjects showed higher indices of both V_{UCM} and V_{ORT} during the accurate production of total force with two fingers which was the sign of task difficulty for elderly. Likely, in our study young group showed lower V_{UCM} and V_{ORT} values than both active and inactive older groups. It can be interpreted that VBS movement was an easier task to show smaller variance indices during the motion for young group in comparison with the older groups.

Higher V_{UCM} seen in older group, could be explained by different postural strategies between young and older groups. Force control is impaired in ankle plantar flexors elderly (160) and strength of ankle stabilizers decreases with age (158). Therefore, ankle strategy weaken in the elderly and they need to compensate their postural control with hip strategy (157). The elderly in our study might compensate the decreased ankle strategy with the usage of lower extremity anterior proximal muscles and therefore used the hip strategy. The involvement of the hip joint means higher degrees of freedom to control during task. This redundancy increases motor flexibility during postural control of the task and leads to increase good variance (V_{UCM}) (161) .

5.3.2 Variance Orthogonal to the UCM (V_{ORT})

The pattern of V_{ORT} was demonstrated during the phases of the sway cycle (see Figure 3.5 for the phases of the sway cycle) for each group in Figure 4.6. V_{ORT} value of master athletes and young sedentary group decreases around the posterior peak (posterior-to-anterior return) of the motion. However, there is no decline, even there is a slight increase, in the V_{ORT} value of older sedentary group during posterior-to-anterior return. Master athletes and young sedentary group decreased their bad variance (V_{ORT}) during the difficult part of the motion (posterior-to-anterior return); however, bad variance (V_{ORT}) of older sedentary group did not decline, even slightly increased during the posterior-to-anterior return which is accepted as the difficult part of the motion.

Since older sedentary group could not decline their bad variance $V_{ORT,}$ they demonstrate stereotypic movement i.e., rigid, not flexible. Master athletes showed more flexible control during the sway cycle by increasing and decreasing their bad variance during the difficult and non-difficult phases of the motion. However, the strategy of older sedentary group seems to keep their bad variance (the variance component that changes the stability of motor output) stable to achieve the task by not risking the stability. This situation decreases the possibility of giving corrective responses to postural perturbations and increases the risk of fall. Moreover, this kind of rigid body control strategy is not cost efficient.

V_{ORT} values are ranked from highest to lowest among the three groups as follows: master athletes, older sedentary group, young sedentary group, where all group differences were significant (Figure 4.5). The lowest V_{ORT} value seen in young sedentary group could be explained by the “task difficulty” case mentioned above with the reference of the study of Wu et al. (159). As a result of keeping V_{ORT} values stable but lower than master athletes, older sedentary group had significantly less V_{ORT} values in the total sway cycle

5.3.3 Synergy Index (ΔV)

The pattern of ΔV (synergy index) was demonstrated during the phases of the sway cycle (see Figure 3.5 for the phases of the sway cycle) for each group in Figure

4.7. For all groups, ΔV value increases around anterior peaks (anterior-to-posterior returns) and the posterior peak (posterior-to-anterior return) of the motion. All subjects' synergy index values increase during the difficult parts of the motion. As the difficulty of task increases, synergy index increases (162).

It is important that the synergy index increases in difficult tasks as well as decreases in movement changes or the beginning of movement. Anticipatory synergy adjustment (ASA), defines the postural strategy that the synergy index suddenly drops in the moment of quick change in the performance variable (163, 164). Anticipatory synergy adjustment (ASA) provides the pre-adjustments of a synergy for sudden alterations in the performance variable (163). In a more flexible motor control system, postural stability needs to be temporarily removed by ASA which is stated as an index related to motor control ability (163). According to ASA phenomenon, it is expected to see sudden and obvious drops in synergy index before the quick movement changes which are corresponding to the times between anterior and posterior peaks in our VBS motion sway cycle (almost around 25% and 75% of the sway cycle). In Figure 4.7, there was a sudden and obvious drop in ΔV values during the times between anterior and posterior peaks for young sedentary group and master athletes. Nevertheless, older sedentary group's ΔV drops were not as sharp as the other groups' ΔV drops. This may be interpreted that older sedentary group applied less flexible motor control strategies during the sudden postural alterations in comparison with young sedentary group and master athletes.

Synergy index (ΔV) values are ranked from highest to lowest among the three groups as follows: older sedentary group, young sedentary group and master athletes, where all group differences were significant (Figure 4.8). As a result of the small ΔV drops during VBS sway cycle, older sedentary group had the highest value of synergy index. VBS movement might be more difficult task for older sedentary group; since the difficulty of task increases, synergy index increases (162). Master athletes had the higher V_{UCM} but the highest V_{ORT} mean value which gives them more flexible motor control character; therefore, they had the lowest ΔV.

We hypothesized that synergy index (ΔV) may be higher in the young sedentary group than in the older sedentary group (15, 16, 17) and may be higher in the master runners than in the older sedentary group (14). In the study of Wang and the others (14) involving healthy older adults, it has been reported that the dancer group who has been dancing for the last five years used higher synergy index in comparison with the non-dancer, regular walker group during preparation for stepping in response to support surface translation. In studies examining the age-related changes of different multiple muscle synergies, such as preparing to step over an obstacle (15), stepping in response to support surface perturbation (16), maintaining balance during support surface perturbation (17), experimental data has showed that the synergy index decreases with age. Two hypotheses were disproved and the findings explained with several other studies. Since the synergy index is a variable that rises and drops in various phases, what types of movement phases the above studies include and which parts of the movements are included in the analysis may affect the results.

5.4 Effect of Lower Limb Laterality on Muscle Synergies

5.4.1 Variance Within the UCM (V_{UCM})

When the pattern of V_{UCM} during the sway cycle is compared among dominant, non-dominant and two-legs-together conditions, it is seen that, V_{UCM} value increases around the posterior peak of the motion for all groups for all the three conditions (right panel of the Figure 4.9). So, in all three conditions, expected V_{UCM} value increases around the difficult part of the motion seems to be valid.

In Figure 4.9, V_{UCM} values were not significantly different for master athletes and older sedentary group in the dominant side; however, master athletes had significantly higher mean V_{UCM} values than older sedentary group in the non-dominant side. If the dominant side is responsible from *motor execution* and the non-dominant side responsible from *stabilizing* according to the Peters's (7) *lower limb laterality* definition, may be the dominant and non-dominant legs show different multi-muscle synergy features based on their different functions during postural control. In this example, when we could not see any difference between V_{UCM} values master athletes and older sedentary group in the dominant side, master athletes had significantly higher mean V_{UCM} values than older sedentary group in the non-dominant side. Master athletes maybe use their non-dominant leg more intensely or more skillfully in terms of *stabilizing* function during VBS movement in comparison with their inactive peers (older sedentary group). If analysis was done only for dominant side, this difference between active and inactive older groups of non-dominant side would have been overlooked. So, it may be interpreted that the possible differences in multi-muscle coordination between right and left (dominant vs. non-dominant) limbs should not be neglected.

On the other hand, V_{UCM} values and patterns the three groups of two-legs-together condition shows similarity with the values and patterns of non-dominant side, rather than dominant side.

5.4.2 Variance Orthogonal to the UCM (V_{ORT})

In the right panel of the Figure 4.10, in the dominant side, master athletes and young sedentary group decreased their bad variance (V_{ORT}) during the difficult part of the motion (posterior-to-anterior return); however, bad variance (V_{ORT}) of older sedentary group did not decline, even slightly increased during the posterior-to-anterior return.

In the non-dominant side, V_{ORT} value of young sedentary group increases just before the posterior peak (posterior-to-anterior return) of the motion. This increase in V_{ORT} value just before the peak motion could be interpreted as Anticipatory synergy adjustment (ASA), the postural strategy that the synergy index suddenly drops in the moment of quick change in the performance variable (163), i.e., increasing V_{ORT} value to decrease ΔV. However, master athletes and older sedentary group increase their V_{ORT} value after then the posterior-to-anterior return, in non-dominant side. This could be interpreted as difference in the ASA phenomenon between young and older groups, in non-dominant side.

As seen in the left panel of the Figure 4.10, V_{ORT} value were ranked from highest to lowest among the three groups as follows: master athletes, older sedentary group and young sedentary group, where all differences were significant except young sedentary and older sedentary groups in non-dominant side.

In two-legs-together condition, V_{ORT} patterns of all groups were similar with the dominant side condition (in the right panel of the Figure 4.10). On the contrary,

V_{UCM} patterns of all groups were similar with the non-dominant side condition (in the right panel of the Figure 4.9). This differences between the representations of two-legs-together condition by dominant and non-dominant sides for V_{ORT} and V_{UCM} should be further investigated and interpreted.

5.4.3 Synergy Index (ΔV)

When the pattern of ΔV during the sway cycle is compared among dominant, non-dominant and two-leg-together conditions, it is seen that, ΔV value of the all groups increases around the posterior peak (posterior-to-anterior return) of the motion for all groups for all the three conditions (the right panel of the Figure 4.11) in convenient with the claim that as the difficulty of task increases, synergy index increases (162).

Additionally, the right panel of the Figure 4.11 was examined in the perspective of Anticipatory Synergy Adjustment (ASA). According to ASA phenomenon, it is expected to see sudden and obvious drops in synergy index before the quick movement changes which are corresponding to the times between anterior and posterior peaks in our VBS motion sway cycle (almost around 25% and 75% of the sway cycle). It was seen that older sedentary groups' ΔV drops were not as sharp as the other groups' ΔV drops in dominant side. On the other hand, master athlete groups' ΔV drops were not as sharp as the other groups' ΔV drops in non-dominant side. Therefore, as a result of these mild drops in ΔV value, older sedentary group had the highest mean ΔV value for the total sway cycle in dominant condition and likewise, master athletes had the highest mean ΔV value for the total sway cycle in non-dominant condition as seen in the left panel of the Figure 4.11.

6. CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The purpose of this study is to investigate motor control mechanisms providing coordination of voluntary dynamic lower extremity movements of the human body under the effects of “natural aging” and "participation in regular exercise" (aerobic running effort for this study). Furthermore, it is also aimed to reach the information about the effect of regular exercise on dynamic movement coordination in the elderly. For this purpose, neuromuscular control strategies followed by the central nervous system during the coordination of lower extremity during repetitive performances of a daily-life motion “voluntary body sway” are investigated in healthy older physically active group (master athletes) and healthy sedentary groups (young and older). Bilaterally selected lower extremity muscles are measured electrophysiologically by surface electromyography (sEMG) method during the aforementioned movement in order to determine muscle activity magnitude-time changes. Ground reaction forces are also recorded simultaneously by the force platform to correlate with motor output. In order to quantify motor coordination strategies, some hypothetical variables claimed to reflect the characteristics of hierarchically structured human motor control mechanism, i.e., “muscle modes” and “synergy index” are calculated analytically according to "Hierarchical Control of Movement (Muscle Synergies) Hypothesis" (Latash, 2008). Principal Component Analysis (PCA) is used to determine muscle modes and examine reciprocal or co-activation strategies followed by muscle modes in the formation of movement. The synergy index is determined with the Uncontrolled Manifold (UCM) Hypothesis. In addition, the results of the UCM analysis for the dominant side were compared for the first time with the non-dominant side. The main findings of the study can be listed as below:

- There was no age or exercise effect on the number of muscle modes. The same number of muscle modes used by all participant groups (master athletes, young and older sedentary groups) during multi-muscular coordination of the repetitive VBS movement. The repetitive VBS movement can be explained by at least 3 principal components (PCs) for all participant groups,

- There was no age or exercise effect on the composition of muscle modes. All participants of the all groups (except one participant from master athletes) demonstrated reciprocal contraction pattern during multi-muscular coordination of the repetitive VBS movement,
- The young sedentary group had significantly lower values for UCM variance components than the older groups, probably depending on experiencing the lowest task difficulty,
- Synergy index ranked from highest to lowest among the three groups as follows: older sedentary group, young sedentary group, master athletes,
- Older sedentary group showed less flexible, more rigid motor control strategies,
- UCM variance components and synergy index values were different in the multi-muscle coordination of dominant and non-dominant lower extremity.

The results of the study are important in terms of revealing the effect of age and exercise on multi-muscle control during a dynamic movement and discussing the difference between the dominant the non-dominant sides of multi-muscle control. Re-examining the VBS movement by dividing it into phases was recommended to reach more detailed information about muscle synergy patterns. It was revealed that the differences in multi-muscle coordination between dominant and non-dominant limbs should not be neglected.

6.2 Recommendations

The main recommendations for further studies can be listed as below:

- With this thesis study, it was revealed that the differences in multi-muscle coordination between dominant and non-dominant limbs should not be neglected. Even, new definitions may be required to differentiate the muscle synergies of dominant and non-dominant limbs i.e., we suggest “*Motor Execution Synergy*” vs. “*Stability Synergy*” to describe limb laterality approach in muscle synergy analyzes.
- Muscle synergy analyzes on non-dominant side could be elucidative for neurologic disease groups or fall prediction studies in terms of investigating

multi-muscle coordination of non-dominant limb which is claimed to be responsible for *stabilization* during postural tasks.

- Re-examining the VBS movement by dividing it into phases, i.e., anterior phases and posterior phase, was recommended to reach more detailed information about muscle synergy patterns. Since UCM variance components and synergy index are variables rising and dropping in various phases of the movement, phase-based analytical and statistical examination seems to be important for further studies.
- Co-contraction Index (CCI) calculations (165) are recommended for future analysis of this data to crosscheck with the results of muscle mode composition i.e., co-activation level.

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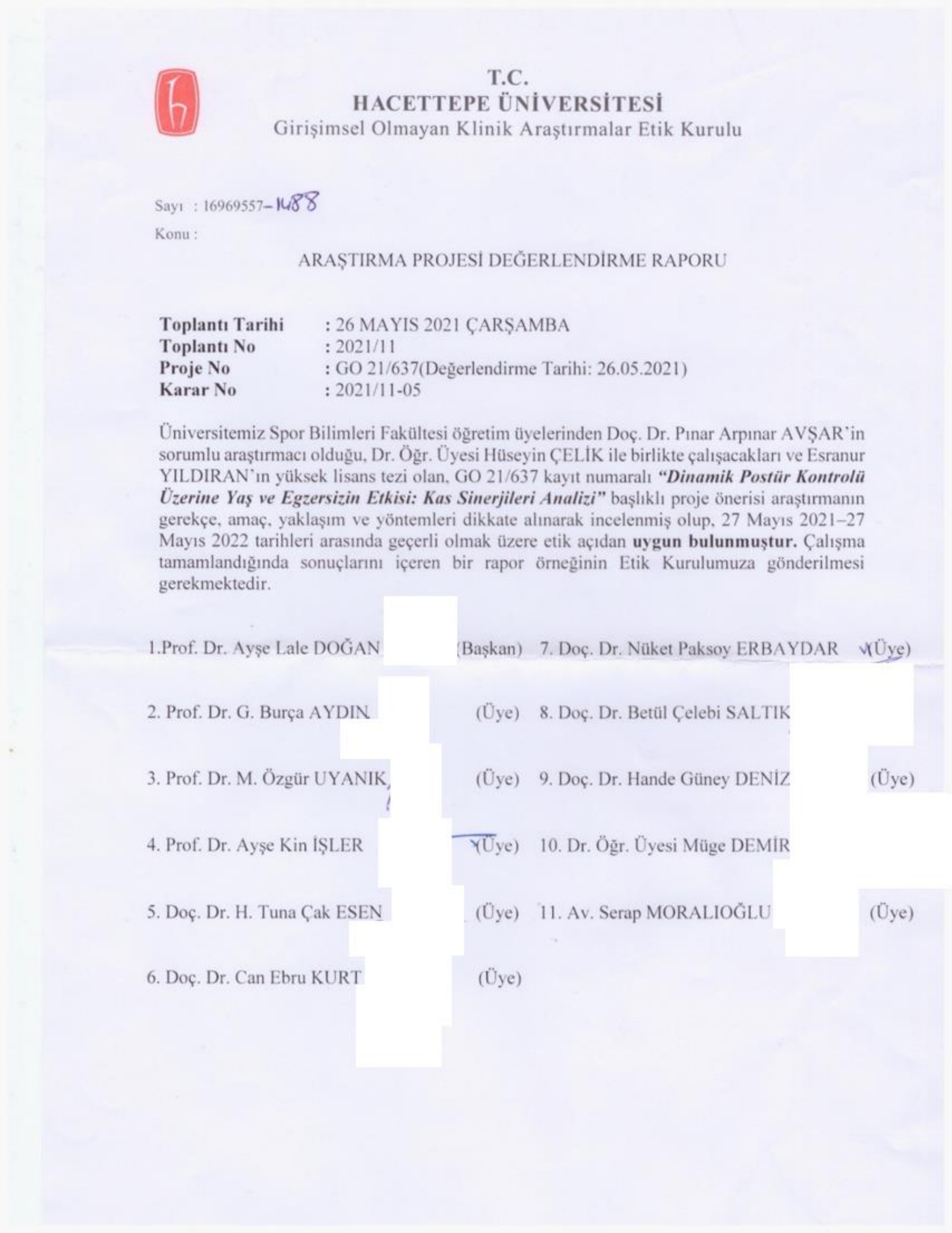
8. APPENDIX

APP 1. Ethical Approval of Hacettepe University Non-Invasive Ethics Committee



T.C.
HACETTEPE ÜNİVERSİTESİ
Girişimsel Olmayan Klinik Araştırmalar Etik Kurulu

Sayı : 16969557-1488
Konu :

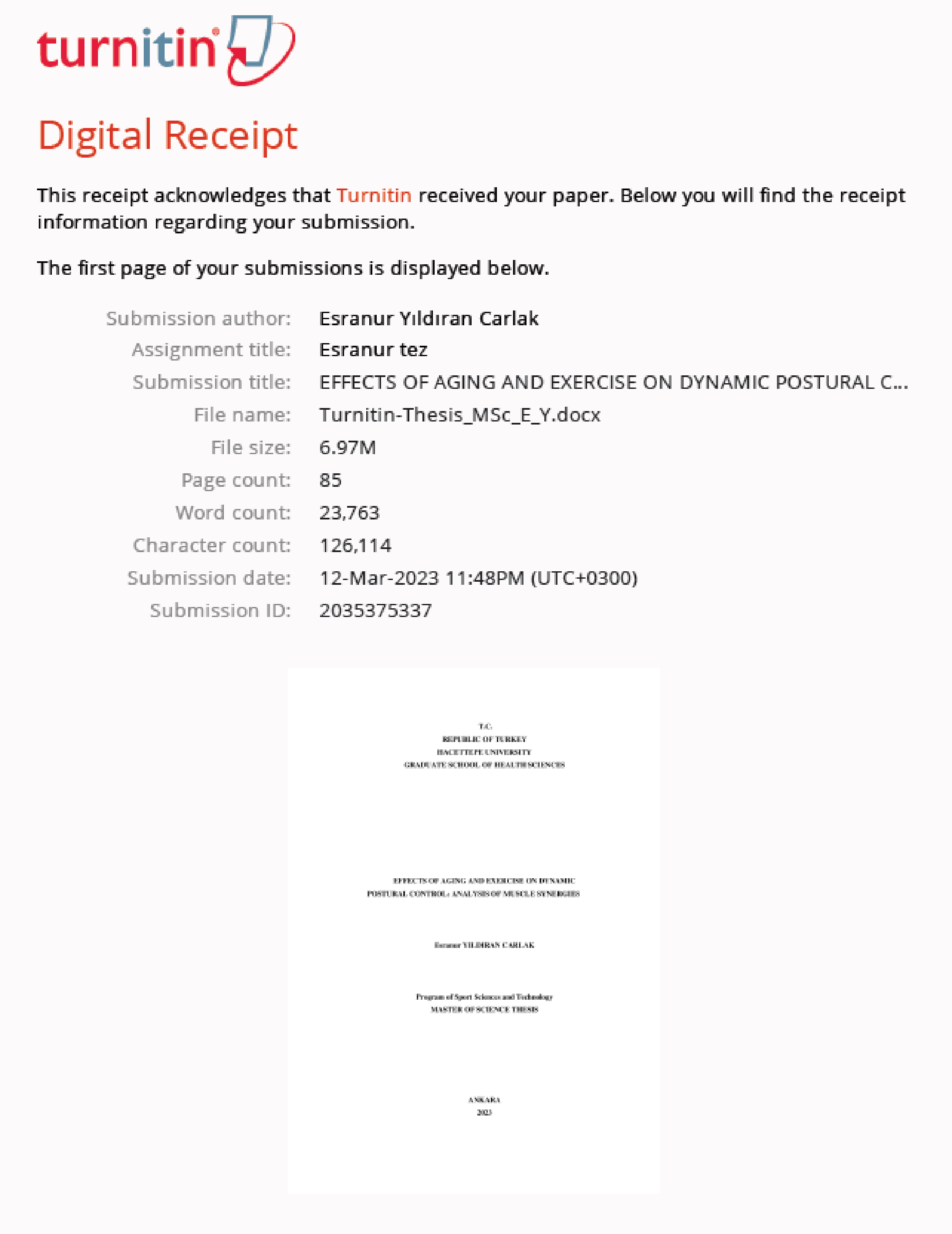
ARAŞTIRMA PROJESİ DEĞERLENDİRME RAPORU

Toplantı Tarihi : 26 MAYIS 2021 ÇARŞAMBA
Toplantı No : 2021/11
Proje No : GO 21/637(Değerlendirme Tarihi: 26.05.2021)
Karar No : 2021/11-05

Üniversitemiz Spor Bilimleri Fakültesi öğretim üyelerinden Doç. Dr. Pınar Arpınar AVŞAR'in sorumlu araştırmacı olduğu, Dr. Öğr. Üyesi Hüseyin ÇELİK ile birlikte çalışacakları ve Esranur YILDIRAN'ın yüksek lisans tezi olan, GO 21/637 kayıt numaralı ***"Dinamik Postür Kontrolü Üzerine Yaş ve Egzersizin Etkisi: Kas Sinerjileri Analizi"*** başlıklı proje önerisi araştırmanın gerekçe, amaç, yaklaşım ve yöntemleri dikkate alınarak incelenmiş olup, 27 Mayıs 2021–27 Mayıs 2022 tarihleri arasında geçerli olmak üzere etik açıdan **uygun bulunmuştur.** Çalışma tamamlandığında sonuçlarını içeren bir rapor örneğinin Etik Kurulumuza gönderilmesi gerekmektedir.

1.Prof. Dr. Ayşe Lale DOĞAN [redacted] (Başkan)	7. Doç. Dr. Nüket Paksoy ERBAYDAR (Üye)
2. Prof. Dr. G. Burça AYDIN [redacted] (Üye)	8. Doç. Dr. Betül Çelebi SALTIK [redacted]
3. Prof. Dr. M. Özgür UYANIK [redacted] (Üye)	9. Doç. Dr. Hande Güney DENİZ [redacted] (Üye)
4. Prof. Dr. Ayşe Kin İŞLER [redacted] (Üye)	10. Dr. Öğr. Üyesi Müge DEMİR [redacted]
5. Doç. Dr. H. Tuna Çak ESEN [redacted] (Üye)	11. Av. Serap MORALIOĞLU [redacted] (Üye)
6. Doç. Dr. Can Ebru KURT [redacted] (Üye)	

APP 2. Thesis Work Digital Receipt and Originality Screen Printout



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REPUBLIC OF TURKEY
HACETTEPE UNIVERSITY
GRADUATE SCHOOL OF HEALTH SCIENCES

EFFECTS OF AGING AND EXERCISE ON DYNAMIC
POSTURAL CONTROL: ANALYSIS OF MUSCLE SYNERGIES

Esranur YILDIRAN CARLAK

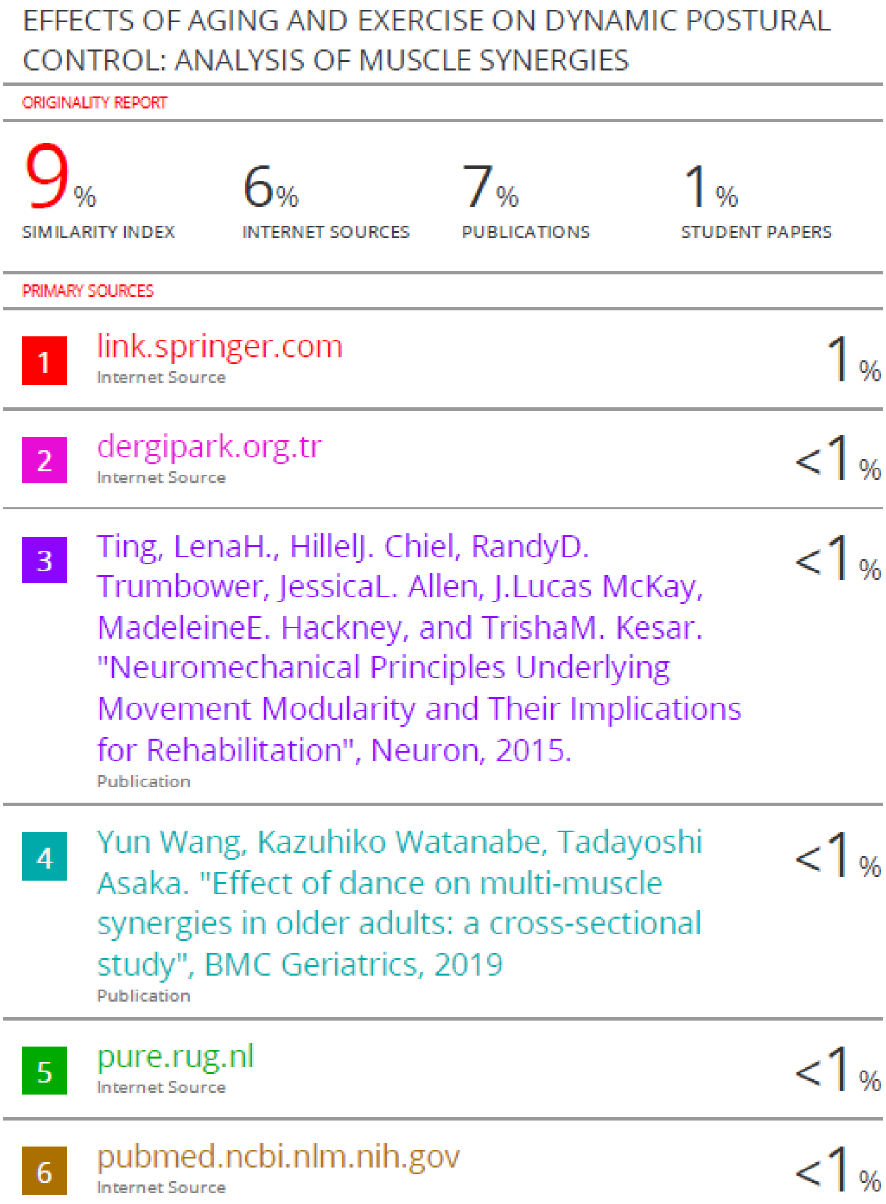
Program of Sport Sciences and Technology
MASTER OF SCIENCE THESIS

ANKARA
2023

EFFECTS OF AGING AND EXERCISE ON DYNAMIC POSTURAL CONTROL: ANALYSIS OF MUSCLE SYNERGIES

Esranur YILDIRAN CARLAK

85 Pages



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APP 3. Informed Consent Form

ARAŞTIRMA AMAÇLI ÇALIŞMA İÇİN AYDINLATILMIŞ ONAM FORMU

Araştırma Projesinin Adı:	Dinamik Postür Kontrolü Üzerine Yaş ve Egzersizin Etkisi: Kas Sinerjileri Analizi
Sorumlu Araştırmacı:	Dr. Pınar Arpınar Avşar Spor Bilimleri Fakültesi, B Blok, Biyomekanik ve Motor Kontrol ABD
Diğer Araştırmacılar:	Dr. Hüseyin Çelik, Esranur Yıldıran Carlak

Araştırmacıların Açıklaması: Bu çalışma kapsamında, çok eklemli yapıdaki insan vücudunun gerçekleştirdiği istemli dinamik hareketlerin koordinasyonunun sağlanmasında bir strateji olarak merkezi sinir sisteminin kullandığı ileri sürülen kas sinerjileri üzerinde yaş alma ve egzersizin etkilerini, çok tekrarlı oturmadan ayağa kalkma ve istemli vücut salınımı hareketleri üzerinden incelemeyi amaçlıyoruz. Yöntemin detaylarını aşağıda bulabilirsiniz.

Sizi bu araştırmaya katılmaya davet ediyoruz. Bu araştırmaya katılıp katılmamakta serbestsiniz. Çalışmaya katılım gönüllülük esasına dayalıdır. Kararınızdan önce araştırma hakkında sizi bilgilendirmek istiyoruz. Bu bilgileri okuyup, varsa sorularınızı bize yönelterek, içeriğini tam olarak anladıktan sonra araştırmaya katılmak isterseniz lütfen formu imzalayınız.

1. **Çalışmanın Amacı:** Araştırmanın amacı, çok eklemli yapıdaki insan vücudunun gerçekleştirdiği istemli dinamik hareketlerin koordinasyonunun sağlanmasında bir strateji olarak merkezi sinir sisteminin kullandığı ileri sürülen kas sinerjileri üzerinde yaş alma ve egzersizin etkilerinin incelenmesidir. Egzersizin dinamik hareketler sırasında yaş almış bireylerde koordinasyon üzerine etkisine dair bilgiye ulaşılması da amaçlanmaktadır.

2. **İzlenecek Yöntem:** Araştırmaya gönüllü olarak katılmayı kabul etmeniz durumunda, Hacettepe Üniversitesi, Spor Bilimleri Fakültesi, Biyomekanik ve Motor Kontrol ABD'nı bir (1) kez ziyaret etmeniz istenecektir.
   Bu ziyaretinizde, kuvvet platformu üzerinde çok tekrarlı iki farklı hareketi hem sağ hem sol taraftan 8'er farklı alt ekstremite kasından yüzeyel EMG ile ölçüm alınırken gerçekleştirmeniz istenecektir. Ölçümler kapsamında; oturma pozisyonundan ayağa kalkma hareketini 3 dakikalık dinlenme süreleriyle 5 x 5 tekrar, istemli vücut salınımı hareketini ayakta dik duruştan sadece ayak bileğinin hareketiyle erişilebilen en uzak anterior ve posterior lokasyonlar arasında ters sarkaç hareketini 3 dakikalık dinlenme arasıyla 2 x 60 sn ardışık tekrarlı olarak, metronom ile işitsel olarak verilen ritmi koruyarak gerçekleştirmeniz istenecektir.

3. **Kullanılacak yöntem, oluşabilecek rahatsızlıklar ve riskler:** Ölçümde yer alan hareketlerin günlük hayat aktivitelerinden oluşması ve dinlenme süreleri içermesi nedeniyle katılımcılarda herhangi bir sağlık sorununa neden olması beklenmemektedir. Ağrı, ayak bileği burkulması, nefes almada güçlük, halsizlik gibi herhangi bir rahatsızlık hissederseniz testi hemen sonlandırmanız önerilmektedir.

   a. Hareketler sırasında kas aktivitesi ölçümü için yüzeyel elektrotlar deri üzerine anti alerjik bant ile yapıştırılacaktır. Test sonunda kolayca ve zarar vermeden deri yüzeyinden ayrılmaktadır.

   b. Protokollerde tekrarlar arasında dinlenme periyodları bulunmaktadır. Ancak, ani gelişen fiziksel bir zorlanma (ağrı, ayak bileği burkulması, nefes almada güçlük gibi) ya da halsizlik gibi bir şikayetiniz olursa ölçümün hemen sonlandırılması için araştırmacıya bilgi veriniz. Böyle bir durumda herhangi bir sorumluluk altına girmeksizin çalışmadan çıkarılmanız sağlanacaktır.

4. **Faydalar:** Araştırma sonuçlarının motor kontrol alanında çok eklemli yapıdaki insan vücudunun gerçekleştirdiği istemli dinamik hareketlerin koordinasyonunun sağlanmasında alt ekstremite kas sinerjilerinin anlaşılmasına katkı sunması hedeflenmektedir. Araştırma protokolü için gönüllü katılımcılardan elde edilecek veriler kayıt edilecek ve genel bir sonuca ulaşmak için tüm katılımcılara ait verilerin istatistiksel analizler ile değerlendirilecektir. Bulgular rapor edilerek ulusal ve uluslararası bilim çevreleri ile paylaşılacaktır.

Veriler bireysel olarak yorumlanmayacaktır. Ancak, araştırma sonunda size bireysel sonuçlarınıza ait bir rapor verilecektir. Bu verilere göre istemli dinamik hareketlerdeki koordinasyonunuzla ilgili fikir sahibi olabilirsiniz.

5. **Araştırmanın ve Ölçümlerin Süresi:** Araştırma kapsamında Hacettepe Üniversitesi, Spor Bilimleri Fakültesi, Nöromusküler Kontrol Laboratuvarını bir (1) kez ziyaret etmeniz istenecektir. Ziyaretinizin süresi yaklaşık 1 saat olacaktır.

6. **Araştırma İzinleri:** Araştırma öncesinde Hacettepe Üniversitesi Girişimsel Olmayan Etik Kurul'a araştırma önerisi sunularak etik kurul izni alınmıştır (Onay Tarih: 26.05.2021, No: 2021/11-05).

7. **Verilerin Gizliliği:** Çalışmaya katılımınız gizli tutulacaktır. Size ait veriler bir kod numarası ile saklanacaktır. Sonuçların yayınlanması ya da araştırmadan çıkan bilgilerin sunulması durumunda, antropometrik veriler dışında katılımcıya ait isim ve tanımlayıcı bilgi paylaşılmayacaktır.

8. **Soru Sorma Hakkı:** Araştırmaya ilişkin her türlü konuda soru sorma hakkınız vardır. Lütfen araştırma sorumlusu Dr. Pınar Arpınar Avşar ile Hacettepe Üniversitesi, Spor Bilimleri Fakültesi B Blok'ta bulunan çalışma ofisinde ya da …. numaralı telefondan ulaşarak soru ve düşüncelerinizi iletiniz.

9. **Katılım Bedeli:** Ulaşım masrafınız ve araç giriş ücreti dışında, araştırmaya katılımınız karşılığında herhangi bir ödeme yapılmayacaktır. Sizden herhangi bir ücret talep edilmeyecektir. Katılımcılar araştırmaya gönüllülük esasına göre dahil edilecektir.

10. **Gönüllü Katılım:** Katılımcılar araştırmaya gönüllülük esasına göre dahil edilecektir. İstediğiniz zaman araştırmadan çekilme hakkına sahipsiniz. Yanıtlamak istemediğiniz herhangi bir soruyu yanıtlamak zorunda değilsiniz. Araştırmadan çekildiğiniz takdirde herhangi bir ceza, sorumluluk ya da yaptırım söz konusu olmayacak, araştırma ekibi ya da araştırmanın gerçekleştiği kurumun size karşı tutumu ve ilişkileriniz etkilenmeyecektir.

11. **Olası Sağlık Sorunları:** Ölçümler esnasında oluşan bir sağlık sorunu durumunda en yakın sağlık kuruluşuna sevk edilmeniz sağlanacak ve masraflar karşılanacaktır.

Araştırmaya katılmak için 18 yaşından büyük olmanız gerekmektedir. Yukarıda yer alan bilgiler ışığında araştırmaya katılmayı kabul ediyorsanız lütfen aşağıda "katılımcı" olarak size ayrılan alanda istenilen bilgileri doldurup araştırmaya katıldığınız tarihi yazarak imzalayınız.

Katılımcı Beyanı

Dr. Pınar Arpınar Avşar ve araştırmacılar tarafından araştırma hakkında tatmin edici şekilde bilgilendirildim. Yukarıda yazılı olarak açıklanan bilgiler bana sözel olarak da aktarıldı. Sorularım yanıtlandı. Bu bilgilerden sonra böyle bir araştırmaya "katılımcı" olarak davet edildim.

Eğer bu araştırmaya katılırsam araştırmacılar ile aramda kalması gereken bana ait bilgilerin gizliliğine bu araştırma sırasında da büyük özen ve saygı ile yaklaşılacağına inanıyorum. Araştırma sonuçlarının eğitim ve bilimsel amaçlarla kullanımı sırasında kişisel bilgilerimin ihtimamla korunacağı konusunda bana yeterli güven verildi.

Projenin yürütülmesi sırasında herhangi bir sebep göstermeden araştırmadan çekilebilirim. (Ancak araştırmacıları zor durumda bırakmamak için araştırmadan çekileceğimi önceden bildirmemim uygun olacağının bilincindeyim) Ayrıca tıbbi durumuma herhangi bir zarar verilmemesi koşuluyla araştırmacı tarafından araştırma dışı tutulabilirim.

Araştırma için yapılacak harcamalarla ilgili herhangi bir parasal sorumluluk altına girmiyorum. Bana da bir ödeme yapılmayacaktır.

İster doğrudan ister dolaylı olsun araştırma uygulamasından kaynaklanan nedenlerle meydana gelebilecek herhangi bir sağlık sorunumun ortaya çıkması halinde, her türlü tıbbi müdahale için ilgili sağlık kuruluşuna yönlendirileceğim konusunda gerekli güvence verildi.

Araştırma sırasında bir sağlık sorunu ile karşılaştığımda; herhangi bir saatte, Dr. Pınar Arpınar Avşar'ı bu formda verilen iletişim yollarından herhangi birisi ile ulaşabileceğimi biliyorum.

Bu araştırmaya katılmak zorunda değilim ve katılmayabilirim. Araştırmaya katılmam konusunda zorlayıcı bir davranışla karşılaşmış değilim. Eğer katılmayı reddedersem, bu durumun araştırmacılar ile olan ilişkime herhangi bir zarar getirmeyeceğini de biliyorum.

Bana yapılan tüm açıklamaları ayrıntılarıyla anlamış bulunmaktayım. Kendi başıma belli bir düşünme süresi sonunda adı geçen bu araştırma projesinde "katılımcı" olarak yer alma kararını aldım. Bu konuda yapılan daveti gönüllülük içerisinde kabul ediyorum.

İmzalı bu form kağıdının bir kopyası talep etmem halinde bana verilecektir.

Adı, soyadı:

Adres:

Telefon:

Tarih:

İmza*:

(*Form toplam 4 sayfadan oluşmaktadır. Okuyup onayladığınızı kabul ettiğinizin göstergesi olarak lütfen diğer sayfaları da imzalayınız.)

Sorumlu Araştırmacı

Adı, soyadı: Dr. Pınar Arpınar Avşar

İmza:

Katılımcı kod numarası: …….. (bu alan araştırmacı tarafından doldurulacaktır)

APP 4. Factor Loadings Tables of Each Participant for Both 3 PCs and 4 PCs (for Dominant Side)

Young Sedentary Group (4 PCs)

S1						S16					
D/ND	Muscles	PC1	PC2	PC3	PC4	D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**0.92**	-0.18	0.14	-0.08	Dominant	*TA*	**0.83**	0.09	0.38	-0.07
	SOL	-0.41	0.38	-0.32	**0.76**		*SOL*	-0.46	-0.04	-0.45	**0.64**
	GM	-0.30	0.38	**-0.83**	0.26		*GM*	-0.33	0.10	-0.31	**0.84**
	RF	**0.82**	-0.21	0.23	-0.31		*RF*	**0.85**	0.13	0.22	-0.28
	VL	**0.86**	-0.21	0.19	-0.24		*VL*	**0.86**	0.11	0.08	-0.33
	VM	**0.88**	-0.20	0.21	-0.24		*VM*	**0.86**	0.11	0.06	-0.31
	BF	-0.19	**0.91**	-0.26	0.20		*BF*	0.18	**0.98**	-0.05	0.05
	ST	**-0.58**	**0.56**	-0.27	0.36		*ST*	-0.21	0.08	**-0.85**	0.39

S17						S18					
D/ND	Muscles	PC1	PC2	PC3	PC4	D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**-0.83**	0.00	0.03	-0.16	Dominant	*TA*	**0.88**	-0.08	-0.11	0.30
	SOL	**0.71**	0.10	0.10	-0.07		*SOL*	**-0.55**	**0.54**	0.30	-0.31
	GM	**0.86**	0.01	0.03	0.12		*GM*	-0.25	**0.87**	0.08	-0.17
	RF	0.04	**0.99**	0.02	0.07		*RF*	**0.68**	-0.24	-0.23	**0.53**
	VL	0.06	0.02	**0.99**	0.06		*VL*	0.47	-0.18	-0.12	**0.77**
	VM	0.25	0.08	0.06	**0.94**		*VM*	0.24	-0.20	-0.11	**0.90**
	BF	**0.83**	0.02	0.07	0.25		*BF*	0.00	**0.79**	0.32	-0.15
	ST	**0.83**	-0.02	-0.01	0.27		*ST*	-0.20	0.31	**0.90**	-0.14

S19						S20					
D/ND	Muscles	PC1	PC2	PC3	PC4	D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**0.91**	-0.05	-0.15	-0.03	Dominant	*TA*	**0.83**	-0.24	0.18	-0.29
	SOL	**-0.67**	0.03	0.36	**0.53**		*SOL*	-0.18	**0.88**	-0.12	0.31
	GM	-0.35	0.43	0.14	**0.79**		*GM*	-0.17	**0.88**	-0.13	0.29
	RF	**0.88**	0.00	-0.20	-0.27		*RF*	0.38	-0.13	**0.90**	-0.08
	VL	**0.86**	-0.07	-0.19	-0.28		*VL*	**0.81**	-0.33	0.27	-0.09
	VM	**0.88**	-0.02	-0.18	-0.26		*VM*	**0.73**	-0.20	0.43	-0.19
	BF	0.00	**0.98**	0.02	0.18		*BF*	-0.40	0.46	-0.12	**0.74**
	ST	-0.29	0.03	**0.94**	0.14		*ST*	-0.43	**0.81**	-0.08	-0.05

S24						S25					
D/ND	Muscles	PC1	PC2	PC3	PC4	D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**-0.72**	0.38	-0.19	0.23	Dominant	*TA*	**0.73**	-0.01	-0.36	-0.27
	SOL	**0.66**	-0.29	0.45	-0.16		*SOL*	-0.22	**0.90**	0.18	0.14
	GM	0.19	-0.23	**0.89**	-0.09		*GM*	-0.21	**0.89**	0.19	0.21
	RF	-0.19	0.33	-0.13	**0.91**		*RF*	**0.91**	-0.23	-0.11	-0.13
	VL	-0.27	**0.76**	-0.14	0.24		*VL*	**0.89**	-0.24	-0.08	-0.16
	VM	-0.14	**0.88**	-0.10	0.16		*VM*	**0.90**	-0.22	-0.09	-0.10
	BF	**0.85**	-0.11	0.26	-0.07		*BF*	-0.21	0.32	**0.89**	0.16
	ST	**0.48**	0.01	0.74	-0.10		*ST*	-0.28	0.31	0.18	**0.89**

S26						S27					
D/ND	Muscles	PC1	PC2	PC3	PC4	D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**0.65**	0.15	-0.05	**-0.60**	Dominant	*TA*	0.46	-0.19	-0.07	**0.86**
	SOL	-0.16	**0.87**	0.15	0.23		*SOL*	-0.19	0.45	**0.79**	0.06
	GM	-0.19	**0.90**	-0.04	0.06		*GM*	-0.17	0.18	**0.92**	-0.13
	RF	**0.83**	-0.11	-0.08	-0.16		*RF*	**0.88**	-0.11	-0.15	0.18
	VL	**0.85**	-0.21	-0.07	-0.06		*VL*	**0.87**	-0.15	-0.16	0.19
	VM	**0.83**	-0.21	-0.07	-0.03		*VM*	**0.91**	-0.07	-0.12	0.16
	BF	-0.08	0.45	-0.01	**0.82**		*BF*	-0.11	**0.92**	0.23	-0.09
	ST	-0.13	0.06	**0.99**	0.01		*ST*	-0.14	**0.90**	0.27	-0.13

S34						S35					
D/ND	Muscles	PC1	PC2	PC3	PC4	D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**0.86**	-0.14	-0.26	0.19	Dominant	*TA*	-0.14	0.17	**0.95**	0.11
	SOL	-0.26	0.47	0.20	**0.76**		*SOL*	**0.87**	-0.18	0.14	-0.11
	GM	-0.18	**0.93**	0.06	0.20		*GM*	**0.86**	-0.21	-0.10	-0.09
	RF	**0.85**	-0.21	-0.16	-0.29		*RF*	-0.19	**0.88**	0.14	0.08
	VL	**0.86**	-0.23	-0.10	-0.28		*VL*	-0.19	0.31	0.12	**0.91**
	VM	**0.84**	-0.22	-0.16	-0.32		*VM*	-0.13	**0.76**	0.08	0.34
	BF	-0.23	0.13	**0.94**	0.13		*BF*	**0.85**	-0.05	-0.14	-0.10
	ST	-0.47	**0.61**	0.35	0.28		*ST*	**0.86**	-0.12	-0.26	-0.09

Young Sedentary Group (3 PCs)

S1						S16					
D/ND	Muscles	PC1	PC2	PC3		D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.91**	-0.17	0.16		Dominant	*TA*	**0.80**	0.12	0.32	
	SOL	-0.46	0.40	**-0.68**			*SOL*	**-0.49**	-0.04	**-0.76**	
	GM	-0.28	0.34	**-0.85**			*GM*	-0.39	0.12	**-0.79**	
	RF	**0.84**	-0.21	0.36			*RF*	**0.86**	0.13	0.34	
	VL	**0.87**	-0.21	0.29			*VL*	**0.88**	0.10	0.27	
	VM	**0.89**	-0.20	0.31			*VM*	**0.89**	0.10	0.24	
	BF	-0.18	**0.90**	-0.35			*BF*	0.18	**0.98**	-0.09	
	ST	**-0.59**	**0.56**	-0.43			*ST*	-0.17	0.04	**-0.89**	

S17						S18					
D/ND	Muscles	PC1	PC2	PC3		D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**-0.84**	-0.03	0.03		Dominant	*TA*	**0.79**	0.00	-0.34	
	SOL	**0.66**	0.05	0.07			*SOL*	**-0.58**	**0.51**	0.40	
	GM	**0.86**	0.02	0.03			*GM*	-0.28	**0.84**	0.13	
	RF	0.00	**0.96**	-0.01			*RF*	**0.83**	-0.23	-0.32	
	VL	0.05	0.03	**0.99**			*VL*	**0.89**	-0.23	-0.08	
	VM	**0.48**	0.37	0.19			*VM*	**0.83**	-0.29	0.05	
	BF	**0.86**	0.07	0.09			*BF*	-0.09	**0.82**	0.26	
	ST	**0.87**	0.04	0.01			*ST*	-0.20	0.37	**0.85**	

S19						S20					
D/ND	Muscles	PC1	PC2	PC3		D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.88**	-0.02	-0.13		Dominant	*TA*	**0.84**	-0.26	0.28	
	SOL	**-0.77**	0.25	0.42			*SOL*	-0.24	**0.92**	-0.11	
	GM	-0.48	**0.74**	0.22			*GM*	-0.21	**0.92**	-0.12	
	RF	**0.91**	-0.10	-0.22			*RF*	0.32	-0.14	**0.90**	
	VL	**0.89**	-0.16	-0.21			*VL*	**0.72**	-0.32	0.42	
	VM	**0.91**	-0.10	-0.19			*VM*	**0.70**	-0.21	**0.51**	
	BF	0.05	**0.95**	-0.01			*BF*	**-0.65**	**0.59**	0.00	
	ST	-0.29	0.07	**0.94**			*ST*	-0.30	**0.77**	-0.23	

S24						S25					
D/ND	Muscles	PC1	PC2	PC3		D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**-0.72**	0.45	-0.20		Dominant	*TA*	**0.73**	-0.01	-0.46	
	SOL	**0.66**	-0.34	0.45			*SOL*	-0.21	**0.90**	0.25	
	GM	0.19	-0.24	**0.88**			*GM*	-0.21	**0.89**	0.29	
	RF	-0.15	**0.76**	-0.19			*RF*	**0.90**	-0.23	-0.18	
	VL	-0.27	**0.77**	-0.12			*VL*	**0.89**	-0.25	-0.17	
	VM	-0.15	**0.83**	-0.07			*VM*	**0.90**	-0.22	-0.14	
	BF	**0.84**	-0.14	0.27			*BF*	-0.17	0.29	**0.83**	
	ST	0.47	-0.04	**0.75**			*ST*	-0.32	0.34	**0.66**	

S26					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.79**	-0.06	0.07	
	SOL	-0.14	**0.89**	0.19	
	GM	-0.11	**0.86**	0.05	
	RF	**0.83**	-0.16	-0.10	
	VL	**0.81**	-0.21	-0.13	
	VM	**0.78**	-0.20	-0.13	
	BF	-0.25	**0.70**	-0.16	
	ST	-0.13	0.04	**0.96**	

S27					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.75**	-0.34	0.07	
	SOL	-0.14	0.41	**0.82**	
	GM	-0.20	0.20	**0.89**	
	RF	**0.88**	-0.07	-0.20	
	VL	**0.88**	-0.11	-0.21	
	VM	**0.89**	-0.03	-0.18	
	BF	-0.12	**0.91**	0.26	
	ST	-0.17	**0.89**	0.29	

S34					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.85**	-0.02	-0.25	
	SOL	-0.27	**0.81**	0.19	
	GM	-0.15	**0.89**	0.03	
	RF	**0.85**	-0.35	-0.15	
	VL	**0.86**	-0.35	-0.09	
	VM	**0.84**	-0.37	-0.15	
	BF	-0.23	0.20	**0.94**	
	ST	-0.46	**0.68**	0.33	

S35					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.14	0.21	**0.95**	
	SOL	**0.87**	-0.21	0.14	
	GM	**0.85**	-0.23	-0.10	
	RF	-0.18	**0.78**	0.12	
	VL	-0.19	**0.76**	0.12	
	VM	-0.12	**0.83**	0.07	
	BF	**0.85**	-0.10	-0.14	
	ST	**0.85**	-0.16	-0.26	

Master Athletes (4 PCs)

S2					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.32	0.19	0.41	**0.78**
	SOL	**0.81**	-0.23	-0.35	-0.23
	GM	**0.90**	-0.16	-0.07	-0.21
	RF	-0.30	0.15	**0.89**	0.20
	VL	-0.23	**0.91**	0.19	0.22
	VM	-0.35	**0.54**	0.02	**0.66**
	BF	**0.72**	-0.17	-0.43	-0.28
	ST	**0.80**	-0.27	-0.30	-0.26

S5					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**-0.60**	-0.12	**-0.70**	-0.02
	SOL	0.46	0.17	**0.57**	**0.55**
	GM	0.39	0.26	0.27	**0.78**
	RF	**-0.81**	-0.05	-0.24	-0.34
	VL	**-0.70**	-0.21	-0.44	-0.21
	VM	**-0.80**	-0.20	-0.22	-0.30
	BF	0.16	**0.96**	0.07	0.17
	ST	0.22	0.03	**0.81**	0.43

S6					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**-0.70**	0.12	0.18	0.29
	SOL	**0.90**	-0.02	0.11	-0.07
	GM	**0.91**	-0.05	0.13	-0.07
	RF	-0.37	**0.48**	0.15	0.41
	VL	-0.14	0.13	-0.05	**0.95**
	VM	-0.01	**0.95**	-0.05	0.09
	BF	0.16	0.00	**0.96**	-0.01
	ST	**0.85**	-0.08	0.23	-0.11

S7					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	0.25	0.26	0.10	**0.86**
	SOL	**0.76**	-0.19	-0.03	0.35
	GM	**0.83**	-0.27	-0.14	0.01
	RF	-0.12	**0.67**	0.24	0.45
	VL	-0.09	0.19	**0.97**	0.11
	VM	0.08	**0.87**	0.12	0.12
	BF	**0.72**	0.45	0.06	0.03
	ST	**0.84**	0.32	-0.06	0.10

S8					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.21	0.04	**0.91**	0.27
	SOL	**0.76**	-0.11	-0.28	-0.15
	GM	**0.82**	-0.03	0.03	-0.28
	RF	-0.24	0.11	0.26	0.74
	VL	-0.11	0.18	0.10	**0.86**
	VM	-0.35	**0.74**	0.23	0.25
	BF	**0.49**	**0.70**	-0.18	0.12
	ST	**0.82**	0.08	-0.18	-0.09

S10					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**-0.63**	0.39	0.15	0.24
	SOL	**0.83**	-0.17	-0.03	-0.02
	GM	**0.70**	-0.21	-0.11	-0.41
	RF	-0.26	0.19	0.11	**0.90**
	VL	-0.06	0.15	**0.98**	0.11
	VM	-0.08	**0.93**	0.15	0.17
	BF	**0.72**	-0.08	-0.09	-0.43
	ST	**0.81**	0.19	0.05	-0.14

S11					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.24	0.19	**0.91**	0.16
	SOL	**0.88**	-0.21	-0.08	-0.10
	GM	**0.90**	-0.15	-0.10	-0.05
	RF	-0.16	0.19	0.13	**0.93**
	VL	-0.20	**0.56**	0.26	0.43
	VM	-0.08	**0.93**	0.07	0.11
	BF	**0.79**	0.01	-0.16	-0.18
	ST	**0.71**	0.00	-0.45	-0.13

S12					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	0.34	-0.04	**0.90**	0.21
	SOL	-0.30	0.15	-0.29	**-0.77**
	GM	-0.42	0.09	-0.02	**-0.78**
	RF	**0.85**	-0.07	0.20	0.20
	VL	**0.76**	-0.08	0.20	0.45
	VM	**0.79**	-0.04	0.26	0.38
	BF	-0.22	0.26	-0.15	**-0.81**
	ST	-0.07	**0.97**	-0.04	-0.23

S13					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.07	0.24	**0.94**	-0.09
	SOL	**0.85**	-0.09	-0.11	0.15
	GM	**0.87**	-0.01	0.17	0.17
	RF	-0.01	**0.82**	0.19	-0.11
	VL	0.01	**0.82**	0.02	0.09
	VM	0.13	**0.82**	0.12	-0.17
	BF	0.26	-0.11	-0.09	**0.94**
	ST	**0.78**	0.28	-0.18	0.04

S14					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.40	**0.65**	0.15	0.05
	SOL	**0.85**	-0.11	-0.06	-0.03
	GM	**0.84**	-0.04	0.18	-0.01
	RF	-0.10	**0.81**	-0.01	0.08
	VL	-0.05	0.22	0.06	**0.97**
	VM	0.03	**0.80**	0.02	0.17
	BF	0.15	0.07	**0.97**	0.06
	ST	**0.77**	-0.14	0.12	-0.03

S15					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.23	0.33	0.16	**0.88**
	SOL	**0.81**	-0.14	0.06	-0.13
	GM	**0.81**	-0.31	-0.05	0.07
	RF	-0.12	0.31	**0.92**	0.15
	VL	-0.06	**0.77**	0.20	0.22
	VM	-0.07	**0.87**	0.14	0.11
	BF	**0.84**	0.04	-0.18	-0.16
	ST	**0.86**	0.10	-0.10	-0.17

S31					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**0.93**	-0.09	-0.08	0.08
	SOL	-0.40	0.33	0.22	**-0.76**
	GM	-0.31	0.23	0.29	**-0.83**
	RF	**0.80**	-0.09	-0.10	0.43
	VL	**0.82**	-0.10	-0.15	0.31
	VM	**0.72**	-0.09	-0.16	**0.52**
	BF	-0.11	**0.96**	0.03	-0.25
	ST	-0.16	0.04	**0.95**	-0.26

Master Athletes (3 PCs)

S2					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.32	**0.54**	**0.60**	
	SOL	**0.80**	-0.30	-0.39	
	GM	**0.90**	-0.25	-0.11	
	RF	-0.29	0.15	**0.90**	
	VL	-0.21	**0.86**	0.17	
	VM	-0.35	**0.81**	0.17	
	BF	**0.71**	-0.26	-0.48	
	ST	**0.80**	-0.35	-0.34	

S5					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**-0.69**	-0.03	**-0.50**	
	SOL	**0.52**	0.23	**0.73**	
	GM	0.40	0.42	**0.64**	
	RF	**-0.82**	-0.13	-0.32	
	VL	**-0.74**	-0.21	-0.40	
	VM	**-0.82**	-0.25	-0.27	
	BF	0.16	**0.95**	0.11	
	ST	0.32	0.02	**0.88**	

S6					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**-0.70**	0.29	0.19	
	SOL	**0.90**	-0.08	0.12	
	GM	**0.90**	-0.10	0.14	
	RF	-0.36	**0.64**	0.13	
	VL	-0.23	**0.68**	0.05	
	VM	0.09	**0.81**	-0.15	
	BF	0.17	0.00	**0.94**	
	ST	**0.85**	-0.15	0.23	

S7					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	0.43	0.42	0.47	
	SOL	**0.84**	-0.11	0.10	
	GM	**0.83**	-0.24	-0.16	
	RF	-0.06	**0.73**	0.39	
	VL	-0.14	0.17	**0.89**	
	VM	0.04	**0.87**	0.10	
	BF	**0.67**	0.46	-0.01	
	ST	**0.82**	0.35	-0.09	

S8					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.20	-0.12	**0.87**	
	SOL	**0.76**	-0.06	-0.30	
	GM	**0.83**	-0.13	-0.15	
	RF	-0.27	0.32	**0.66**	
	VL	-0.15	0.48	**0.61**	
	VM	-0.35	**0.68**	0.29	
	BF	0.48	**0.71**	-0.09	
	ST	**0.82**	0.10	-0.19	

S10					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**-0.64**	0.42	0.15	
	SOL	**0.78**	-0.12	-0.02	
	GM	**0.77**	-0.32	-0.12	
	RF	**-0.51**	**0.53**	0.15	
	VL	-0.07	0.17	**0.98**	
	VM	-0.04	**0.91**	0.13	
	BF	**0.81**	-0.22	-0.10	
	ST	**0.83**	0.16	0.05	

S11					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.27	0.16	**0.83**	
	SOL	**0.88**	-0.23	-0.09	
	GM	**0.90**	-0.16	-0.09	
	RF	-0.11	**0.54**	**0.54**	
	VL	-0.19	**0.66**	0.36	
	VM	-0.09	**0.89**	0.00	
	BF	**0.79**	-0.06	-0.23	
	ST	**0.72**	-0.02	-0.45	

S12					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	0.09	-0.18	**0.88**	
	SOL	**-0.73**	0.25	-0.35	
	GM	**-0.86**	0.11	-0.24	
	RF	0.44	0.04	**0.70**	
	VL	**0.64**	-0.03	**0.62**	
	VM	**0.57**	0.02	**0.69**	
	BF	**-0.77**	0.34	-0.20	
	ST	-0.22	**0.94**	-0.05	

S13					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.10	0.21	**0.94**	
	SOL	**0.85**	-0.05	-0.09	
	GM	**0.88**	0.02	0.19	
	RF	-0.06	**0.82**	0.21	
	VL	0.02	**0.80**	0.00	
	VM	0.05	**0.83**	0.16	
	BF	**0.57**	-0.22	-0.25	
	ST	**0.74**	0.33	-0.14	

S14					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.44	**0.59**	0.16	
	SOL	**0.85**	-0.09	-0.06	
	GM	**0.84**	-0.02	0.19	
	RF	-0.15	**0.76**	0.00	
	VL	0.01	**0.63**	0.05	
	VM	-0.01	**0.79**	0.02	
	BF	0.15	0.09	**0.97**	
	ST	**0.77**	-0.12	0.13	

S15					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.30	0.45	**0.54**	
	SOL	**0.82**	-0.16	-0.01	
	GM	**0.80**	-0.29	-0.02	
	RF	-0.08	0.27	**0.88**	
	VL	-0.06	**0.78**	0.27	
	VM	-0.06	**0.87**	0.16	
	BF	**0.84**	0.03	-0.24	
	ST	**0.87**	0.08	-0.17	

S31					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.91**	-0.06	-0.04	
	SOL	**-0.52**	**0.59**	**0.49**	
	GM	-0.45	**0.52**	**0.60**	
	RF	**0.86**	-0.21	-0.23	
	VL	**0.85**	-0.16	-0.22	
	VM	**0.80**	-0.25	-0.33	
	BF	-0.10	**0.95**	0.02	
	ST	-0.15	0.02	**0.94**	

Older Sedentary Group (4 PCs)

S3					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.21	0.06	-0.07	**0.92**
	SOL	0.01	**0.95**	0.05	0.07
	GM	**0.59**	0.42	0.39	-0.21
	RF	**-0.85**	0.13	-0.06	-0.09
	VL	**-0.73**	-0.11	0.09	0.37
	VM	**-0.76**	-0.08	0.03	0.34
	BF	-0.03	0.03	**0.95**	-0.01
	ST	**0.61**	0.35	0.46	-0.19

S4					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.08	0.32	**0.94**	0.00
	SOL	**0.60**	-0.03	0.00	**0.76**
	GM	**0.88**	-0.18	-0.01	0.28
	RF	-0.12	**0.87**	0.10	0.12
	VL	-0.06	**0.86**	0.16	-0.16
	VM	-0.20	**0.81**	0.21	-0.03
	BF	**0.90**	-0.24	-0.14	-0.07
	ST	**0.85**	-0.03	-0.03	0.34

S21					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	0.46	-0.02	**0.86**	-0.12
	SOL	-0.31	0.14	-0.26	**0.83**
	GM	-0.23	**0.52**	-0.08	**0.69**
	RF	**0.77**	-0.03	0.35	-0.39
	VL	**0.93**	-0.11	0.14	-0.15
	VM	**0.83**	-0.02	0.34	-0.32
	BF	0.02	**0.94**	-0.02	0.24
	ST	-0.26	**0.49**	0.08	**0.66**

S22					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	0.25	0.03	-0.02	**0.91**
	SOL	-0.28	0.23	**0.70**	-0.03
	GM	-0.12	-0.23	**0.85**	0.00
	RF	**0.81**	-0.11	-0.02	0.14
	VL	**0.63**	0.08	-0.35	0.39
	VM	**0.79**	0.02	-0.21	0.07
	BF	-0.01	0.45	**0.56**	-0.39
	ST	-0.03	**0.93**	-0.01	0.05

S23					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	0.18	0.11	**0.95**	-0.01
	SOL	-0.44	0.31	0.33	**0.51**
	GM	-0.18	0.25	-0.07	**0.91**
	RF	**0.87**	-0.08	0.06	-0.16
	VL	**0.85**	-0.06	0.09	-0.11
	VM	**0.86**	-0.09	0.09	-0.13
	BF	-0.03	**0.93**	0.05	0.15
	ST	-0.18	**0.88**	0.12	0.22

S28					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	0.16	0.17	-0.02	**0.93**
	SOL	**-0.77**	-0.15	0.29	-0.35
	GM	**-0.93**	-0.12	0.08	-0.02
	RF	0.20	**0.55**	-0.48	0.41
	VL	0.12	**0.87**	-0.02	0.10
	VM	0.10	**0.87**	-0.05	0.11
	BF	-0.09	0.03	**0.91**	0.07
	ST	-0.43	-0.25	**0.62**	-0.34

S29					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.34	**0.73**	0.20	-0.35
	SOL	**0.85**	-0.31	-0.19	0.18
	GM	**0.80**	-0.20	-0.17	0.38
	RF	-0.30	**0.79**	0.29	-0.21
	VL	-0.26	**0.86**	0.22	-0.10
	VM	-0.28	0.42	**0.85**	-0.16
	BF	**0.78**	-0.40	-0.21	0.19
	ST	0.46	-0.31	-0.16	**0.80**

S30					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.14	-0.07	**0.91**	0.28
	SOL	**0.71**	0.04	**-0.50**	-0.30
	GM	**0.75**	0.44	-0.18	-0.23
	RF	-0.38	-0.11	**0.56**	**0.56**
	VL	-0.15	-0.09	0.27	**0.87**
	VM	-0.31	-0.06	0.20	**0.84**
	BF	**0.83**	0.28	-0.08	-0.24
	ST	0.30	**0.94**	-0.07	-0.07

S32					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**0.68**	-0.01	0.15	**0.67**
	SOL	-0.12	**0.78**	-0.42	-0.24
	GM	-0.01	**0.91**	-0.23	0.13
	RF	**0.89**	-0.09	0.11	0.13
	VL	**0.87**	-0.01	0.12	0.18
	VM	**0.92**	-0.09	0.14	0.01
	BF	-0.09	0.27	**-0.91**	0.02
	ST	-0.28	0.39	**-0.75**	-0.20

S33					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.01	0.24	**0.96**	0.12
	SOL	**0.89**	-0.16	0.00	-0.23
	GM	**0.75**	-0.19	-0.02	-0.43
	RF	-0.19	**0.86**	0.19	0.01
	VL	-0.22	**0.82**	0.08	0.10
	VM	0.00	**0.87**	0.10	-0.01
	BF	0.21	0.07	-0.06	**-0.92**
	ST	0.34	-0.13	-0.11	**-0.85**

S36					
D/ND	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	-0.14	0.28	**0.94**	0.12
	SOL	**0.80**	-0.27	-0.22	-0.06
	GM	**0.84**	-0.34	0.02	-0.07
	RF	-0.16	**0.49**	0.16	**0.84**
	VL	-0.13	**0.89**	0.15	0.19
	VM	-0.22	**0.79**	0.26	0.26
	BF	**0.89**	-0.04	-0.05	-0.05
	ST	**0.88**	-0.01	-0.11	-0.15

Older Sedentary Group (3 PCs)

S3					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**-0.59**	0.38	-0.21	
	SOL	0.04	**0.90**	0.10	
	GM	**0.63**	0.38	0.43	
	RF	**-0.70**	-0.01	0.00	
	VL	**-0.83**	-0.05	0.04	
	VM	**-0.84**	-0.04	0.00	
	BF	-0.06	0.03	**0.94**	
	ST	**0.63**	0.33	0.48	

S4					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.07	0.32	**0.94**	
	SOL	**0.85**	0.00	0.03	
	GM	**0.92**	-0.20	-0.03	
	RF	-0.06	**0.88**	0.11	
	VL	-0.11	**0.85**	0.15	
	VM	-0.19	**0.81**	0.21	
	BF	**0.80**	-0.27	-0.18	
	ST	**0.92**	-0.04	-0.04	

S21					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.80**	-0.02	**0.51**	
	SOL	**-0.56**	**0.63**	0.16	
	GM	-0.31	**0.84**	0.03	
	RF	**0.90**	-0.26	-0.02	
	VL	**0.86**	-0.19	-0.06	
	VM	**0.92**	-0.21	-0.01	
	BF	0.11	**0.86**	-0.37	
	ST	-0.26	**0.81**	0.15	

S22					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.70**	-0.04	0.00	
	SOL	-0.22	0.24	**0.71**	
	GM	-0.08	-0.22	**0.85**	
	RF	**0.75**	-0.11	-0.06	
	VL	**0.73**	0.05	-0.37	
	VM	**0.69**	0.02	-0.25	
	BF	-0.19	**0.49**	**0.53**	
	ST	0.03	**0.92**	-0.02	

S23					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	0.17	0.09	**0.95**	
	SOL	**-0.51**	**0.50**	0.31	
	GM	-0.33	**0.64**	-0.11	
	RF	**0.87**	-0.14	0.07	
	VL	**0.84**	-0.09	0.10	
	VM	**0.85**	-0.13	0.10	
	BF	0.03	**0.90**	0.07	
	ST	-0.14	**0.88**	0.14	

S28					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.60**	0.37	0.09	
	SOL	**-0.84**	-0.17	0.28	
	GM	**-0.81**	-0.02	0.13	
	RF	0.37	**0.62**	-0.44	
	VL	0.13	**0.85**	-0.02	
	VM	0.11	**0.86**	-0.04	
	BF	-0.06	0.02	**0.92**	
	ST	**-0.54**	-0.30	**0.60**	

S29					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.43	**0.76**	0.19	
	SOL	**0.83**	-0.27	-0.29	
	GM	**0.88**	-0.22	-0.20	
	RF	-0.34	**0.80**	0.31	
	VL	-0.25	**0.83**	0.28	
	VM	-0.29	0.44	**0.81**	
	BF	**0.76**	-0.36	-0.30	
	ST	**0.76**	-0.47	0.01	

S30					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.26	-0.07	**0.90**	
	SOL	0.35	0.48	**-0.65**	
	GM	0.26	**0.83**	-0.29	
	RF	**-0.57**	-0.29	**0.62**	
	VL	**-0.86**	-0.14	0.28	
	VM	**-0.85**	-0.22	0.26	
	BF	0.29	**0.77**	-0.24	
	ST	0.03	**0.87**	-0.01	

S32					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	**0.83**	0.05	0.24	
	SOL	-0.18	**0.74**	-0.48	
	GM	0.03	**0.92**	-0.23	
	RF	**0.90**	-0.11	0.09	
	VL	**0.88**	-0.02	0.11	
	VM	**0.89**	-0.13	0.09	
	BF	-0.08	0.27	**-0.90**	
	ST	-0.32	0.36	**-0.77**	

S33					
D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.09	0.29	**0.89**	
	SOL	**0.75**	-0.32	0.24	
	GM	**0.81**	-0.27	0.11	
	RF	-0.12	**0.88**	0.15	
	VL	-0.22	**0.82**	0.07	
	VM	0.02	**0.84**	0.13	
	BF	**0.84**	0.18	-0.27	
	ST	**0.87**	-0.06	-0.25	

S36

D/ND	Muscles	PC1	PC2	PC3	
Dominant	*TA*	-0.14	0.32	**0.93**	
	SOL	**0.80**	-0.26	-0.22	
	GM	**0.84**	-0.32	0.02	
	RF	-0.16	**0.85**	0.10	
	VL	-0.14	**0.86**	0.15	
	VM	-0.22	**0.81**	0.26	
	BF	**0.89**	-0.06	-0.05	
	ST	**0.88**	-0.09	-0.10	

APP 5. PCA Analysis Results of Dominant (8 muscles), Non-dominant (8 muscles), Two-legs-together (16 muscles) Conditions

Table 1: Percentage of variance explained by the 4 principal components.

% Variance explained for	**Young Sedentary**	**Master Athlete**	**Older Sedentary**
Dominant 8 muscles (M ± SS)	% 87.0 ± 3.9	% 82.1 ± 4.6	% 83.8 ± 4.6
Non- dominant 8 muscles (M ± SS)	% 86.8 ± 5.4	% 80.8 ± 3.9	% 85.1 ± 6.5
Two-legs-together 16 muscles (M ± SS)	% 75.5 ± 6.6	% 69.9 ± 6.1	% 73.6 ± 7.3

Table 2: Number of total appearances of significantly loaded muscles in each PC for each subject of the three groups for **dominant side**.

	Young Sedentary					**Master Athlete**					**Older Sedentary**				
Dominant	Muscles	PC1	PC2	PC3	PC4	Muscles	PC1	PC2	PC3	PC4	Muscles	PC1	PC2	PC3	PC4
	TA	**10**		1	2	*TA*	4	1	**5**	3	*TA*	1	1	**6**	**4**
	SOL	5	**4**	1	**4**	*SOL*	**9**		1	3	*SOL*	**6**	2	2	3
	GM	1	**5**	**3**	2	*GM*	**9**			3	*GM*	**7**	1	1	2
	RF	**8**	2	2	2	*RF*	3	**4**	2	2	*RF*	**5**	**4**	1	2
	VL	**8**	1		3	*VL*	3	**4**	2	3	*VL*	**5**	**5**		1
	VM	**8**	2		1	*VM*	2	**9**		2	*VM*	**5**	**4**	1	1
	BF	3	**5**	2	2	*BF*	**6**	3	2	2	*BF*	4	2	**4**	1
	ST	4	**3**	**4**	1	*ST*	**9**	1	2		*ST*	3	**4**	2	3

Table 3: Number of total appearances of significantly loaded muscles in each PC for each subject of the three groups for **non-dominant side**.

	Young Sedentary					**Master Athlete**					**Older Sedentary**				
Non-Dominant	Muscles	PC1	PC2	PC3	PC4	Muscles	PC1	PC2	PC3	PC4	Muscles	PC1	PC2	PC3	PC4
	TA	**5**	**1**	**3**	**1**	*TA*	**5**	**1**	**4**	**1**	*TA*			**3**	**1**
	SOL	**5**	**2**	**1**	**2**	*SOL*	**6**			**6**	*SOL*	**3**	**1**		
	GM	**4**	**3**	**1**	**2**	*GM*	**6**	**1**		**5**	*GM*	**3**	**1**		
	RF	**6**	**2**	**1**	**2**	*RF*	**3**	**6**	**2**		*RF*	**2**	**3**		**1**
	VL	**6**	**2**	**1**	**1**	*VL*	**2**	**6**	**2**	**1**	*VL*	**1**	**3**		
	VM	**6**	**2**	**2**	**2**	*VM*	**2**	**6**	**2**	**1**	*VM*	**1**	**2**		**1**
	BF	**2**	**5**	**2**	**2**	*BF*	**4**	**4**	**1**	**2**	*BF*	**1**		**1**	**2**
	ST	**3**	**1**	**5**		*ST*	**6**	**3**	**1**	**1**	*ST*	**2**		**1**	**1**

Table 4: Number of total appearances of significantly loaded muscles in each PC for each subject of the three groups for **two-legs-together condition**.

	Young Sedentary					**Master Athlete**					**Older Sedentary**				
	Muscles	PC1	PC2	PC3	PC4	Muscles	PC1	PC2	PC3	PC4	Muscles	PC1	PC2	PC3	PC4
Dominant	*TA*	**8**	**1**	**2**	**3**	*TA*	**3**	**3**	**3**	**4**	*TA*	**3**	**4**	**4**	**2**
	SOL	**5**	**4**	**5**		*SOL*	**12**	**1**			*SOL*	**8**	**2**		**3**
	GM	**4**	**4**	**5**		*GM*	**11**	**1**	**1**		*GM*	**7**	**2**	**2**	**2**
	RF	**7**	**2**	**4**		*RF*	**4**	**4**	**3**	**1**	*RF*	**4**	**5**	**1**	**1**
	VL	**7**	**3**	**4**		*VL*	**3**	**4**	**4**	**2**	*VL*	**4**	**5**	**1**	**1**
	VM	**7**	**3**	**5**		*VM*	**3**	**4**	**3**	**3**	*VM*	**4**	**5**	**2**	**1**
	BF	**5**	**2**	**3**	**3**	*BF*	**6**	**2**	**3**	**2**	*BF*	**5**	**1**	**2**	**3**
	ST	**6**	**3**	**5**	**1**	*ST*	**10**		**1**	**1**	*ST*	**5**	**2**	**3**	**2**
Non-Dominant	*TA*	**6**	**3**	**1**	**3**	*TA*	**3**	**3**	**4**	**4**	*TA*	**2**	**4**	**6**	**1**
	SOL	**6**	**6**	**2**	**1**	*SOL***	**11**				*SOL***	**8**	**2**		**2**
	GM	**7**	**4**	**2**		*GM*	**11**	**1**	**1**		*GM*	**7**	**2**	**1**	**2**
	RF	**7**	**3**		**2**	*RF*	**1**	**8**	**1**	**1**	*RF*	**4**	**4**	**2**	**1**
	VL	**8**	**4**		**2**	*VL*	**2**	**6**	**1**	**2**	*VL*	**3**	**4**	**2**	**2**
	*VM**	**7**	**3**		**4**	*VM**		**7**	**2**	**3**	*VM**	**2**	**2**		**1**
	BF	**4**	**4**	**3**	**4**	*BF*	**8**	**1**		**5**	*BF*	**5**	**1**	**1**	**5**
	*ST**	**4**	**2**	**3**	**1**	*ST**	**8**		**2**	**3**	*ST**	**2**	**1**	**2**	**1**

* VM and ST muscle were measured with 10 participants from Young Sedentary and Master Athlete groups, and 5 participants from Older Sedentary group. ** SOL muscle was measured with 10 participants from Master Athlete group and 11 participants from Older Sedentary group.

Table 5: Mainly loaded muscle groups in each muscle mode (PC1, PC2, PC3, PC4) of each subject of the three groups; as ventral group (V), dorsal group (D) or ventral-dorsal group together (V-D) for **dominant side.**

	Young Sedentary				**Master Athlete**				**Older Sedentary**			
#	*PC1*	*PC2*	*PC3*	*PC4*	*PC1*	*PC2*	*PC3*	*PC4*	*PC1*	*PC2*	*PC3*	*PC4*
1	V	D	D	D	D	V	V	V	V-D	D	D	V
2	V	D	D	D	V	D	V-D	D	D	V	V	D
3	D	V	V	V	D	V	D	V	V	D	V	D
4	V-D	D	D	V	D	V	V	V	V	D	D	V
5	V	D	D	D	D	V-D	V	V	V	D	V	D
6	V	D	V	D	D	V	V	V	D	V	D	V
7	D	V	D	V	D	V	V	V	D	V	V	D
8	V	D	D	D	V	D	V	D	D	D	V	V
9	V	D	D	V-D	D	V	V	D	V	D	D	V
10	V	D	D	V	D	V	D	V	D	V	V	D
11	V	D	D	D	D	V	V	V	D	V	V	V
12	D	V	V	V	V	D	D	D				

Ventral group includes some or all of TA, RF, VL, VM muscles and dorsal group includes some or all of SOL, GM, BF, ST muscles and ventral-dorsal group includes muscles of both ventral group and dorsal group. The first column represents the number of subjects.

Table 6: Mainly loaded muscle groups in each muscle mode (PC1, PC2, PC3, PC4) of each subject of the three groups; as ventral group (V), dorsal group (D) or ventral-dorsal group together (V-D) for **non-dominant side.**

	Young Sedentary				**Master Athlete**				**Older Sedentary**			
#	*PC1*	*PC2*	*PC3*	*PC4*	*PC1*	*PC2*	*PC3*	*PC4*	*PC1*	*PC2*	*PC3*	*PC4*
1	V	D	D	D	V-D	V	D	D	V	D	D	V
2	V	D	V-D	D	V	D	D	D	D	V	V	V
3	D	V	V	V	D	V	D	V	D	V	V	D
4	D	D	V	V	V	D	V	D	D	V	V	D
5	V	D	V	D	V	D	V	D	D	V	V	D
6	D	V	D	V	D	V-D	V	V				
7	D	V	V	D	V-D	D	V	V				
8	V	D	D	D	D	V	V	D				
9	V	D	D	D	D	V	V	D				
10	V	D	D	V	D	V	V	D				
11					D	V	V	D				

Ventral group includes some or all of TA, RF, VL, VM muscles and dorsal group includes some or all of SOL, GM, BF, ST muscles and ventral-dorsal group includes muscles of both ventral group and dorsal group. The first column represents the number of subjects.

Table 7: Mainly loaded muscle groups in each muscle mode (PC1, PC2, PC3, PC4) of each subject of the three groups; as ventral group (V), dorsal group (D) or ventral-dorsal group together (V-D) for **two-legs-together condition**.

	Young Sedentary				**Master Athlete**				**Older Sedentary**			
#	*PC1*	*PC2*	*PC3*	*PC4*	*PC1*	*PC2*	*PC3*	*PC4*	*PC1*	*PC2*	*PC3*	*PC4*
1	V	D	D	D	D	V	V-D	V	V	D	V-D	D
2	V-D	D	D	V	V-D	D	D	V	D	V	V	V
3	D	V-D	V	V	D	V	V	D	D	V	V-D	V
4	V-D	D	D	V	D	V	V	V	D	V	D	V
5	V	D	V-D	D	D	V	D	V	V	V	D	D
6	D	V	V	V	V-D	V	V-D	V	D	V-D	V	D
7	D	V	V	V	D	V	V	V-D	V	D	V	D
8	V	D	D	V-D	V-D	V	V	D	V-D	V	V	D
9	V	D	D	D	D	V	V	V	D	V	V	D
10	D	V	D	D	D	V	D	V	D	V	V	D
11	V	V-D	D	D	D	V	V	V	D	V	V	V-D
12	D	V	V	V	V	D	D	D				

Ventral group includes some or all of TA, RF, VL, VM muscles and dorsal group includes some or all of SOL, GM, BF, ST muscles and ventral-dorsal group includes muscles of both ventral group and dorsal group. The first column represents the number of subjects.

9. CURRICULUM VITAE