Impact of exercise footwear features on middle-aged and older adults' lower limb muscle activity during gait

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**IMPACT OF EXERCISE FOOTWEAR FEATURES ON MIDDLE-AGED
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GAIT**

VIVEK MANOHARAN

**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

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**SCHOOL OF MECHANICAL AND AEROSPACE
ENGINEERING**

A thesis submitted to the Nanyang Technological University in partial fulfilment
of the requirement for the degree of Doctor of Philosophy

2019

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I hereby certify that the work embodied in this thesis is the result of original research, is free of plagiarised materials, and has not been submitted for a higher degree to any other University or Institution.

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This thesis contains material from one paper published in the following peer-reviewed journal(s) in which I am listed as an author.

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ABSTRACT

Muscle health has been established to decline as a function of age. Owing to this age-related deterioration, it has been noted that older adults (65+ years) exhibit less muscle force production capability during gait, different compensatory mechanisms and co-activation patterns in the lower extremity muscles than young adults. It was noted that studies designed to understand age-related gait muscle activity differences have primarily included subjects of young (20 – 30 years) and older adults (65+ years) but have failed to consider the middle-age (40 – 60 years) group, though muscle strength has been reported to peak and weaken from the fourth decade of life.

Footwear features have been noted to positively affect leg muscle activity patterns during gait, thus could be potentially considered as an intervention to improve muscle health in older adults. In the previous studies that advocate footwear's efficacy in improving lower extremity muscle tone, it was noted the subjects were primarily the younger age group. Inconsistency was also noted in the experimental protocol and data comparison methodology.

Surface electromyography (SEMG) is frequently used to study the effect of footwear features on muscles. However, SEMG signal can be affected by a myriad of factors including placement of electrodes, muscle quality, etc. Considering the highly variable nature of SEMG signals and other inter-subject

variability, the normal practice used to average SEMG signals require further evaluation.

The objective of the project is to identify exercise footwear features that improve lower extremity gait muscle activity in middle-aged and older adults through amplitude and integrated surface electromyography method.

Studies were conducted on fifteen subjects' dominant leg, five from each age-group: young (20 – 30 years), middle-aged (40 – 60 years) and older adults (65+ years). Ten lower-extremity muscles were measured along five different phases of a gait cycle on multiple density (FitFlop™), rocker bottom (MBT™), and barefoot (Adidas Adipure Trainer™) footwear against a normal flat-soled canvas footwear as control (North Star™) using multi-channel SEMG system.

In summary, it was noted that older subjects when compared with younger and middle age control group exhibited lesser activity in the amplitude and integrated EMG (IEMG) scale on peroneus longus and tibialis anterior muscle groups. Inter-subject findings showed that MBT™ rocker bottom shoe had a greater effect on older adults than other age groups. FitFlop™ multiple density type did not significantly differ on all the observed age groups. Among the footwear types compared, Adidas Adipure Trainer™ minimalist-type exhibited the most significant difference in all age groups. Based on intra-subject integrated EMG (IEMG) comparison, popular midsole and outsole features have a localized effect

only on major calf and shin muscles, but not on other key lower-extremity gait muscles. The study highlighted existence of significant differences in results obtained by various SEMG comparison methods. Additive manufacturing methods for faster prototyping of footwear designs were also highlighted

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CHAPTER 1 INTRODUCTION

1.1 Background and motivation

The proportion of adults aged 60 and above is increasing on a global scale. A 2015 UN report estimated that nearly 901 million people in the world) were aged 60 or over, this number predicted to cross 1.4 billion (around 22% of the world population) by the year 2050 [1]. In Singapore, the proportion of residents aged 65 and above, is expected to be around 18.7% of the total population by the year 2030 i.e. 1 in 4 Singaporeans will be aged 65 and above [2, 3].

Advancements in healthcare are expected to drastically increase the average life expectancies in developed countries [4-6]. Muscle mass and strength have been reported to deteriorate directly as a function of age and this deterioration leads to difficulties in performance of basic daily activities in older adults. This deterioration when associated with increasing life expectancies among the older adults, presents a major problem to the healthcare system. Lifestyle comprising of reduced mobility and less exercise aggravates the deterioration of muscle health in the elderly. On the contrary, regular exercise and non-sedentary lifestyle have been widely studied and reported to improve muscle health in the elderly, especially in the lower extremity [4-6].

Studies on exercise preferences among the elderly, showed that majority of them preferred ‘walking’ exercise [7-10]. Walking exercise is known to significantly

improve lower extremity muscle health in the elderly [7-11]. A coordinated series of bone movements makes the human body walk with a locomotion pattern commonly referred as 'gait' [12].

Midsole and outsole based footwear features have been reported to affect lower extremity muscle activity patterns during gait [13-17]. Hence, it can be inferred that certain footwear features could positively influence gait muscle activity patterns during walking exercise and enable the wearer to exercise his/her lower limb muscles optimally. However, a close scrutiny on existing scientific evidence highlights the inconsistencies in the surface Electromyography (SEMG) criteria and statistical protocols considered to infer the features' effect on muscles [13-17]. Effects of popular 'muscle toning' rocker bottom, multiple density and minimalist exercise footwear types have also been concluded by some studies including the one commissioned by American Council on Exercise, to be insignificant to be concluded as effective [16, 18]. It is also noted that the footwear studies' involved primarily focused on a narrower age-group (20 – 40 years) and the EMG methodology routinely involved averaging of the muscle activity across all subjects or a muscle or an age-group into one representative dataset. Then, comparing, analyzing and drawing conclusions based on the representative dataset [13-17]. A representative EMG dataset methodology for comparison ignores the effects of the high variability function owing to high frequency content inherent in an EMG data and other inevitable inter-subject

variability in the quality of muscle owing to biological and lifestyle factors [4, 19-22].

1.2 Objective and Scope

The objective of the project is to identify exercise footwear features that improve lower extremity gait muscle activity in middle-aged and older adults through amplitude and integrated surface electromyography method. The objective would be achieved through the following scope.

- Identify age-related difference on ten lower extremity gait muscles of fifteen young, middle-aged and older adults.
 - Check leg-dominance hypothesis on lower extremity muscle activity (Right versus left) on five young subjects ((20 – 30 years old) on shod (footwear) and unshod (no footwear) condition.
 - SEMG studies were conducted on fifteen subjects, five from each age-group: young (20 – 30 years old), middle-aged (50 – 60 years old) and older adults (65+ years old) on ten lower-extremity muscles through SEMG
 - The results will be used to identify the confounding effect of ageing on muscle activity for further footwear studies
- Evaluate influence of muscle toning footwear features on fifteen young, middle-age and older adults.
 - Studies were conducted on fifteen subjects, five from each age-group: young (20 – 30 years), middle-aged (50 – 60 years) and older adults (65+ years) on ten lower-extremity muscles along five different phases of a gait cycle on multiple density (FitFlop™), rocker bottom (MBT™), and barefoot (Adidas Adipure Trainer™) against a normal flat-soled canvas footwear as control (North Star™).
 - Compare amplitude versus integrated EMG (IEMG) methods, intra-subject versus inter-subject variability and its effect on results obtained

- The data will be used to recommend footwear features for older and middle-aged adults.

1.3 Contributions

The impact of exercise footwear features in middle-aged and older adults has been barely addressed by the scientific community. Evidence suggests that midsole and outsole features affect gait muscle activity, but primarily focussing on a younger-age group [23-29]. This project's approach quantified and compared the effect of midsole and outsole features on middle-aged and older adults against a younger age group. The contributions of the project can be summarised as

1. In-depth and rigorous SEMG based comparison of gait muscle activity on ten key lower extremity muscles on various midsole and outsole features during a gait cycle.
2. Analysing the effect of age-related changes in the lower extremity gait muscle activity and the influence of midsole and outsole footwear features on the above.
3. The EMG methodology routinely involved averaging of the muscle activity across all subjects or a muscle or an age-group into one representative dataset. Then, comparing, analyzing and drawing conclusions based on the representative dataset, which could lead to differences in inferences concluded [1-5]. This project rigorously

compared the effect of difference SEMG methodologies including subject variability and method variability. The results highlighted the effect of SEMG method and concluded that the differences observed could be affected by the method and subject conditions. The impact of these differences would enable future SEMG-based footwear studies to consider an intra-subject approach rather than an inter-subject comparison.

4. A review-based scoring system was developed for additive manufacturing techniques was done to suggest faster prototyping of footwear features in the future.

The following articles were accepted/published:

- EMG-based comparison of intra- and inter-subject variation in lower extremity gait muscle activity for various footwear types, V Manoharan, SM Chou, G Chai, S Forrester and P Kong accepted in 2nd International Conference in Sports Science & Technology, Singapore, 2016.
- Effect of popular exercise footwear on the gait muscle activity of middle - aged and older adults: preliminary findings, V Manoharan, SM Chou, G Chai, S Forrester and P Kong in 1st International Conference in Sports Science & Technology, Singapore, 2014.
- Application of additive manufacturing techniques in sports footwear. V Manoharan, SM Chou, S Forrester, GB Chai - Virtual and Physical Prototyping, 2013.

1.4 Hypotheses to be tested

Based on literature review, the following hypotheses were made

- Presence of a leg-dominance effect in lower extremity muscle activity.
- Age-related differences can be observed in the lower-extremity gait muscle activity among young, middle-aged and older adults.
- Midsole and outsole footwear features affect lower-extremity muscle activity differently across age-groups.
- Different SEMG data analysis methodologies have varied effect on the results obtained: Amplitude analysis versus integrated EMG analysis, intra-subject versus inter-subject differences.

1.5 **Organization of report**

The report covers description the various parts of the project on literature review, hypothesis formulation, experimental methodology formulation and validation.

Chapter one briefly introduces the background through a brief overview of global ageing population scenarios and motivation behind the project to address and improve muscle health among older adults.

Chapter two will briefly cover the basics of ageing muscle, gait analysis, gait muscle activity parameters, gait analysis variables, relevant SEMG methodology for experimental studies.

Chapter three will cover a review of existing studies on SEMG based gait analysis, age-related differences in muscle activity, effect of footwear features.

Chapter four will cover the hypothesis formulation and methodology of experimental SEMG studies conducted.

Chapter five will cover the summary of results and discussions obtained from the chapter four's SEMG studies.

Chapter six will cover conclusions, limitations and future work from the author based on studies.

CHAPTER 2 BASICS OF AGING MUSCLE, GAIT AND ELECTROMYOGRAPHY

It has been well-established that muscle property and strength changes with age. Human locomotion primarily involves precise execution of muscle patterns; hence it is important to understand the accurate relation between the effects of age-related muscular property changes and its manifestation on human locomotion patterns.

In the following sections, literature review on structural and functional changes in muscle properties due to ageing and its consequences will be discussed.

2.1 Skeletal muscles and gait

Skeleton gives rigidity, support and framework to the human body. Skeletal muscles are voluntarily controlled muscles that attach to bones across skeletal joints via tendons; as the muscle contracts it generates a ‘pull’ force and moves the bones about the joint [30, 31].

Contractions of skeletal muscles are the primary mechanism responsible for human locomotion. The muscles are innervated through motor neurons arising from the spinal cord, the motor neurons interface with the muscle fibers through motor units (MUs) at neuromuscular junctions as shown in figure 2-1. After receiving neural signals from the central nervous system (CNS), the motor unit sends action potentials across the muscle fibers causing it to contract, thereby

producing a ‘force’, this force creates or resists motion of the bone along the joint involved. The contractions can be coordinated by CNS to form complex motion including walking.

Figure 2-1. The muscles are innervated through motor neurons arising from the spinal cord, the motor neurons interface with the muscle fibers through motor units (MUs) [7].

‘Gait’ is defined by the Oxford Dictionaries™ as “a person’s manner of walking”. Human walking involves a complex coordination of muscle activity, especially in the lower extremity.

Gait is normally analyzed and compared based on the following parameters [30, 32, 33]

- **Temporal -Spatial variables** – stride time, speed, cadence, stride length, stride width, stance duration etc.

- **Kinematic variables** – Joint flexion angles, Joint extension angles, Hip rotational angle, foot pronation angles, centre of mass motion etc.
- **Kinetic variables** – Ground reaction forces, joint moments, joint power, peak power, etc.
- **Plantar pressure** – Measurement of distribution of pressure over the foot.
- **Muscle activity** – Electrical motor unit action potentials (MUAPs) recorded and analyzed through electromyography. The coordination of muscular activity, along with skeletal motion during walking forms a unique cyclic pattern referred as the ‘gait cycle’. A gait cycle can also be defined as the time period between consecutive heel strikes of the same leg. A two-dimensional gait cycle of a leg consists of two basic phases, *stance phase* and *swing phase* [9]. Human gait cycle

Figure 2-2. A typical two-dimensional human gait cycle (R. - Right Leg, L. - Left leg) [32].

is primarily alternating stance and swing phase between legs i.e. when the right leg is in swing phase, left leg would be in stance phase. 20% of gait cycle comprises of overlap between right and left leg stance phases (illustrated in figure 2-2).

- **Stance phase** – comprises 60% of gait cycle period and are generally categorized by five main events
 - Initial contact of the foot with a heel strike.
 - Entire plantar surface of the foot comes in contact with the ground
 - Middle of the stance phase characterized single limb support of weight, foot flat on the ground while the rest of the body is moving forward.
 - Heel is off the ground.
 - Toe push off and beginning of the swing phase.
- **Swing phase** – Actual body propulsion happens at this phase and comprises 40% of gait cycle time period and are categorized by three main events
 - Foot lifted off the ground through flexing of knees.
 - Foot is on the air and tibia is perpendicular to the ground.
 - From mid-swing phase to the heel strike (beginning of the consecutive stance phase).

2.2 Structural & functional role of a muscle fiber

Schematic organization of a skeletal muscle is illustrated in figure 2-3. Sarcomere is the basic contraction unit of a muscle fiber (myocyte or myofiber). Sacromeres are made up of myosin (thick) and actin (thin) filaments. Myosin filament consists of globular heads extending outwards towards actin filaments.

Figure 2-3. Schematic organization of a skeletal muscle [9].

On receiving action potential from CNS, calcium ions are released from the sarcoplasmic reticulum and those ions bind with the troponin molecules resulting in a structural change to the actin filaments, thus causing the myosin heads to form cross-bridges with actin filaments (in the presence of ATP) as illustrated in figure 2-4. As long as ATP is present, the cross-linking occurs continuously [34]. The cross-bridges bend to create a pulling force on the actin filaments to the

centre of the sarcomere, thus causing a contraction of the muscle fibre and muscle as a whole.

In a sarcomere, actin and myosin protein filaments are involved in active muscle production, but for additional stability and passive production of internal tension proteins like titin, elastin, collagen, etc are utilized [31, 34].

Figure 2-4. Illustration of Actin and Myosin contraction inside a muscle fiber [32].

Maximum muscle activity during gait cycle happens in the lower extremity muscles and is illustrated in figure 2-5 (Relative intensity of EMG during gait cycle) [35].

Figure 2-5. Relative intensity of EMG during a gait cycle [32].

2.2.1 Contribution of lower extremity muscles in a gait cycle

Muscles of interest in the lower extremity were systematically identified based on their contribution to support based on gait's vertical ground reaction force (GRF) during the gait cycle and their role in locomotion through key kinematic events of the gait cycle. Previous studies on general age-related lower extremity muscle activity differences have not indicated a systemic methodology for choosing muscles of interest. Studies focusing on specific muscle groups was either chosen for a pathological reason or based on functional role of the muscle.

Support – muscle contributions to ground reaction force

Muscle activity of the lower extremity is one of the contributors to the ground reaction forces during gait [36]. Based on Anderson et al.'s three-dimensional muscle-actuated model of the human body for normal walking [37], it was found that;

- Ankle dorsiflexors, gluteus maximus, vasti, and posterior gluteus medius/minimus generated the majority of support in early stance.
- Posterior gluteus medius and minimus supported the body during the midstance
- Soleus and gastrocnemius generated nearly all support during the late stance.

- Hamstrings, erector spinae, internal oblique, external oblique, rectus femoris, adductor magnus and iliopsoas showed large forces but contributed less to support.

Other studies have also indicated same muscles as primary contributors to ground reaction forces [32, 38, 39]. A diagrammatic illustration of the muscles indicated above

is given in appendix 1.1. These muscles contract to contribute to the kinematic movements in three anatomical planes as illustrated in figures 2-6 and 2-7.

Figure 2-6. Anatomical planes of the human body [32].

Figure 2-7. Lower limb kinematics during typical gait cycle, the curve is presented as mean $\pm$ 1 SD [34].

Since role of skeletal muscles are prominent in the initiation of gait, any structural

and functional change in muscles would be manifested in the gait patterns.

2.3 Structural and functional changes in a skeletal muscle due to ageing

A structural and functional change of a muscle fibre significantly affects its force production capacity. Key age-related structural and functional changes can be divided into aspects. According to the 2015's UN's report on ageing, 25 to 59 years were classified as young and middle-aged, 60 and above as older adults [1].

- **Strength** - Based on comparative studies between young and elderly subjects muscle strength was substantially lower in older adults, on average 39% decline in isometric strength compared with younger adults [11, 34].
- **Structure** - Reduction in skeletal muscle cross-sectional area (CSA) upto 32 % in women, 40% in men of ages 80 – 90, this is primarily attributed to the decrease in number of muscle fibers, sarcomeres and small reduction in the size of fast twitch muscle fibers [4, 34].
- **Reduction in muscle quality (MQ)** – MQ is defined as the muscle strength per unit muscle CSA or unit muscle mass; reduction in MQ has been associated with aging [40]. It was also reported that loss of muscle strength with aging occurred more rapidly than the loss of muscle mass, thus it was suggested that the quality of the muscle fibers may have been primarily responsible for exhibited loss in muscle strength rather than the loss of muscle mass and cross sectional area [41].

- **Composition** - Increase in non-contractile elements of the muscle (tissues not involved in active force production i.e. fat and other connective tissues) content and decrease in the contractile element (tissues involved in active muscle production)[40]. Despite the increase of non-contractile elements with age, muscle cross-sectional area is noted to decrease [40].
- **Physiological changes** - reduced ratio between synthesis of proteins and their breakdown is noted to decrease as age progresses, this decrease is also attributed to be the cause of reduction in the muscle mass [4]. Decreased muscle fiber to capillary ratio and reduced oxidative capacity of skeletal muscles are also noted with progression of age [4].
- **Neural changes** - reduction in number of MUs innervating the muscle fibers and motor unit potentials generated [4, 11, 19, 42]. Some studies have indicated reduction in firing rate of MUs and it has been attributed to loss of nervation in type II or fast twitch fibers and sharing of the neighboring type I or slow twitch MU nerves by the type II fibers, thereby causing an overall reduction in production of force [4, 34]. Reduction in the number of motor neurons of about 29% by the age 90 [34].

2.4 Gait related consequences of Sarcopenia & Dynapenia

A review article by Luca [11] noted that the term Sarcopenia is generally used to describe age-related changes that occur within skeletal muscle and thus encompasses the effects of altered central and peripheral nervous system innervation, altered hormonal status, inflammatory effects, and altered caloric and

protein intake. These multiple factors all contribute to sarcopenia and to the characteristic skeletal muscle atrophy and weakness, both of which are considered major contributing factors to the loss of functional mobility, independence, and frailty present in many older adults (a descriptive illustration of factors and mechanisms contributing to sarcopenia is presented in figure 2-8).

Definition for ‘sarcopenia’ is not thoroughly established, based on definitions presented in the literature, sarcopenia can be generally associated with loss of muscle mass and strength with age,

Figure 2-8. Illustration of factors and mechanisms contributing to sarcopenia. Image source - [10]

However, another article [14] argued that age-related loss of muscle strength cannot be completely correlated with loss of muscle mass as defined by sarcopenia. It proposed the term ‘dynapenia’ to characterize age dependent loss in muscle strength and power, which were attributed to other mechanisms (neural, muscular, etc) along with loss of muscle mass. Dynapenia is now widely used to describe loss of muscle strength with age. The effect of sarcopenia and dynapenia is recognized by the medical community to be debilitating and life threatening in older adults. Effects of conditions sarcopenia and dynapenia would be evident in gait parameters of the elderly.

Loss of muscle mass was reported to be greater in lower extremity muscles than rest of the body [40]. This can be attributed to sarcopenia and might affect functional performance of gait. In a comparative study between the young and elderly, it was estimated that by the seventh and eighth decade of life, adults lose about 20% – 40% of knee extensor strength, similar loss of strength was also reported in ankle plantar and dorsiflexor muscles [40]. Sarcopenia/dynapenia in the old age was also associated with higher metabolic costs, decrease in lower extremity muscle strength, muscle power, reduced gait speed and double support time in the gait cycle [20, 43, 44].

2.5 Lifestyle, exercise and muscle health in the older adults

In the previous chapter, deterioration of muscle health with age, sarcopenia, dynapenia and its effect on gait muscle activity were discussed. In this section, the effect of lifestyle and exercise on muscle health in older adults will be discussed.

2.5.1 Lifestyle and other related factors affecting muscle health of older adults

Regular physical activity has been noted to be a major factor in preventing deterioration of muscle health, in older adults, regular physical activity of about 30 minutes per day improved conditions like sarcopenia and arthritis [45]. In a West European study, it was noted that only one in five above the age of 75 years did the physical activity of recommended 2.5 hours per week [45]. Genetic factors accounted nearly 50% – 60% muscle health loss in sarcopenia [46].

Participation in physical activity is a complex process influenced by many factors like health condition, lack of interest, fear of injury, social support, weather, infrastructure etc [45]. Based on literature review, the following lifestyle factors were identified to majorly contribute to sarcopenia, dynapenia and loss of muscle health [45-50].

- Physical inactivity
- Cigarette smoking
- Alcohol consumption
- Underweight
- Nutrition
- Testosterone

2.5.2 Effect of exercise on muscle health of older adults

It was established in previous sections that force generation capability of muscles significantly decreases owing to structural and functional changes with age. Effects of exercise and training on ageing muscle will be discussed in this section.

Exercise has been widely reported to slow down and ‘partially’ reverse the deterioration of muscle health and improve functional performance in older adults [4-6]. High intensity resistance exercises significantly increased muscle force production capabilities in the old age group [4-6].

Williams et al. pointed out a common misconception about older adults ‘taking it easy’ when exercising, older adults respond to resistance and strength training similar to young adults, hence can be suggested a strength training or resistance based program [4]. Endurance and strength training also increased muscle’s capillarization, oxidative capacity, cross sectional area in older adults [4].

Though strength and endurance training improved old age group muscle’s structural and functional capabilities, old age groups are more prone to injury and soreness during exercise than the young [4]. Structurally weak muscles in older adults are also prone to faster damage than that of the young group [4].

Walking has been the most preferred and recommended exercise among older adults owing to its nature of being a less strenuous exercise [7-10]. Regular walking exercise improves muscle functional health and lower extremity strength in older adults [10, 51]. Lack of a comfortable footwear, blisters and foot pain

was reported to be perceived barriers for choosing walking as physical activity [52].

Previous sections focused on age-related differences in gait muscle activity. In this section, methodology and equipment used in measuring age-related gait muscle activity shall be discussed.

2.6 Requirements of a locomotion measurement system

Some of key requirements to be noted in choosing a measurement system for gait studies [53].

1. Noninvasiveness - the measurement system should not interfere intrude or cause changes to the quantity measured. It should not disturb the movement of the subject anyway. It should cause minimum inconvenience to the subject.
2. Validity – the system’s results should exactly reflect the variable that is intended to measure.
3. Reliability – accuracy and precision of the system should be statistically adequate.
4. Repeatability – the results obtained from the system should be reproducible provided the same conditions.
5. Real time data presentation – this would serve as a feedback for the experimenters, thus ensuring more control of the study.
6. Affordable price
7. Ease of calibration

Based on the above criteria, a commonly used tool to analyze neuromuscular electrical activity in gait, is electromyography (EMG) [54-57]. Kinematics of lower extremity joints are sometimes measured through motion analysis cameras to analyze gait [58]. However, kinematic movement and kinetics of a particular joint is controlled by more than one muscle, overlapping or compensatory muscle activity might occur in executing a kinematic event, therefore analyzing kinematics of gait cycle may not directly reflect the extent of muscle activity during gait. Plantar only indirectly reflects muscle activity or correlates with muscle health deterioration. Thereby, a more direct approach for measuring muscle health and activity is preferred.

EMG records myoelectric signals during gait thereby analyzing muscle actions directly responsible for locomotion [55]. EMG can be used to analyze muscle force, muscle fatigue, speed of contraction, muscle synergy, muscle based temporal data, etc. Multichannel surface EMG (SEMG) systems can record multiple muscles at the same time. Repeatability of SEMG signals across various geographic locations has been verified and established [59]. Since mechanism of muscle contraction is primarily based on myoelectric activity i.e. muscle action potentials (AP) generated by the motor unit (MU) traveling through the muscle fiber thereby causing the contraction of the muscle. This contraction is primarily responsible for the muscle force generated. EMG technique will be used to pick up and record the myoelectric signals (motor unit action potentials) propagating through the muscle, thereby indirectly measuring the muscle force. A slight delay

of about 50ms was noted between start of muscle electric activity and development of muscle force [60].

2.7 Use of Surface EMG in gait muscle activity studies

Surface EMG (SEMG) primarily picks up the motor unit action potentials (MUAP) of a muscle from the surface of the skin through electrodes as illustrated in figure 2-9.

Figure 2-9. Detecting motor unit action potentials through surface EMG electrodes [4].

MUAPs are generated from the motor unit. SEMG signals picked up from the skin represent a superposition of MUAPs firing patterns (illustrated in figure 2-10). Since SEMG picks up MUAP signals from the surface of the skin, the skin layers will have low pass filter effect. Signals recorded are merely a reflection and superimposition of MUAPs, but does not directly represent the original features of MUAPs in the muscle.

Figure 2-10. Interference and superposition of MUPAs as detected by SEMG [4].

2.7.1 Validity of SEMG technique

Muscle force depends upon recruitment of MUs and firing rate of MUs. EMG technique detects MU action potentials on the skin surface, the EMG signal's amplitude can be considered an indirect reflection of the muscle force generated. The EMG amplitude - muscle response curve is deemed quasi-linear in most of the cases [61, 62]. SEMG – signal force relationship curve is presented in figure 2-11, Some factors have been noted to affect this relationship include muscle conditioning i.e. trained and muscle conditioned subjects might exert less amount of SEMG activity for the same force than untrained and unconditioned subjects [61]. Other factors affecting this linear relationship include adipose tissue content, electrode location, inclination of fibers, cross talk, co-activation strategies and active MUs [62]. Positioning electrodes near the innervation zone (but not on)

has been recommend to capture SEMG signals that closely represents force behavior of the muscle [62]. Within day variability and consistency of SEMG recordings were good [62]. Shape of EMG profiles across various gait trials was found to be consistent (but varying in magnitude) [55].

2.7.2 Key factors affecting SEMG in dynamic gait analysis

Figure 2-11. Muscle Force - EMG root mean square amplitude relationship curve [4].

A schematic diagram of various factors affecting the SEMG signal and its effect on interpretation is illustrated in figure 2-11. Factors affecting SEMG signal in gait analysis are discussed as follows:

Figure 2-12. Schematic diagram of the factors affecting EMG signal and their relationship with interpretation parameters [9].

- **Tissue thickness** – thickness of the skin, adipose tissue content, tissue type and other biological characteristics differ among human subjects and affect the amplitude of the SEMG signal obtained [61, 63]. Tissue effects can be minimized through proper skin preparation, identification of electrode sites and placement site selection from same researcher.
- **Cross talk** – defined as the interference of adjacent muscle's electrical activity rather than the muscle of interest. Since EMG signals are recorded from the surface, this phenomenon is most prominent in the SEMG technique [61-63].

Cross talk may be eliminated through identifying proper placement sites and appropriate filtering methods [62, 64, 65].

- **External noise** – Should be kept to minimum by choosing appropriate electromagnetic interference free environment and ensuring proper grounding of electrical equipment [63].
- **Electrode site identification and placements** – After extensive studies, electrode site placements has been recommended by organizations like SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) and ISEK (International Society of Electrophysiology and Kinesiology) [66, 67]. It is recommended that the electrode be placed between the MU and the tendon end (avoid extreme positions). The electrode should also be placed in alignment with direction of muscle fibers [55]. Previous studies have recommended placement of electrodes away from innervations zones (IZ) [66, 68]. SENIAM also recommended bipolar SEMG electrodes with an inter-electrode distance of at least 20 mm [66]. No significant difference in magnitude values or EMG profile shape was found between deep and surface SEMG recording [69].
- **Skin preparation and electrode fixation** – Shaving and removal of hair and top keratinized layer of the skin has been noted to reduce skin impedance [55, 66]. Proper electrode fixation is also essential [66]. No difference in EMG magnitude and pattern was found between deep and surface EMG measurement [55].
- **Internal and external disturbances** – Generally, EMG data of first two-three strides and last two-three strides are excluded from the data [70]. If the researcher

feels that a disturbance has caused a deviation from normal gait pattern, it is usually excluded [70].

2.7.3 General SEMG signal processing methodology for gait related studies

SEMG signal processing methods and protocols will be discussed in the following sections.

Identification of gait cycle in the acquired SEMG signal

To normalize and standardize the duration of SEMG activity analyzed during gait, usually EMG activity/profile across a gait cycle (two consecutive heel strikes of the same leg) is considered [19, 54, 70, 71]. A gait cycle can be identified based on kinematic and kinetic related descriptors like heel switches, video camera motion capture, accelerometers, force plates on the ground, infrared marker motion analysis systems, etc and all these systems should be time synchronized with the main SEMG setup [19, 54, 55, 70-73].

Filtering

Raw SEMG signals usually has redundant and unnecessary frequency content including movement artifacts, ECG content and baseline noises, hence filtering of signals is necessary to remove the redundant and unnecessary frequency contents. Agencies like SENIAM (Surface Electromyography for the Non-Invasive Assessment of Muscles) and ISEK (International Society of Electrophysiology

and Kinesiology) have established requirements of filtering frequencies based on the muscles analyzed [74]. Rose reviewed different filtering frequencies available in the literature and collated information on relevant frequencies for various muscles (presented in table 2-1) [74]. However, loss of useful content should be noted and kept to the minimum while employing these envelope filters. Acquired SEMG signal's frequency during normal walking was reported to be around 9 Hz [55].

Table 2-1. Band pass filtering frequencies from selected journal article collated by Rose [70].

Muscle	Frequency_{low} (Hz)	Frequency_{high} (Hz)	Sampling Rate (Hz)
ta, pl, mg, so, tp	40	400	250
ta, mg	6	400	1000
bb	5	1000	2000
bb	10	450	1024
mg, ta	20	800	1000
vl, vm, st, bf	20	450	1000
vl, vm, st, bf, rf, mg	5.5	600	1000
mg, ta	16	600	1000
vl	10	500	1000
ra, d, lmf	10	1000	2000
st, sm, bf	5	1000	2500
st, bf, gm, rf, ta, so, al	150	1000	2500

Muscle abbreviations are al - adductor longus, bb - biceps brachii, bf - biceps femoris, d - deltoid, gm - gluteus maximus, lmf - lumbar multifidus, mg - medialgastrocnemius, ra - rectus abdominis, rf - rectus femoris, sm - semimembranosus, st - semitendinosus, ta - tibialis anterior, tp - tibialis posterior, vl - vastus lateralis, vm - vastus medialis, so - soleus.

Linear envelope and averaging of EMG traces

Linear envelope or smoothing of the EMG signal can be obtained using three techniques; moving average of the signal window, root mean square and 6 Hz Butterworth low-pass filtering [53, 54, 63].

In order to obtain a valid representative EMG trace, it was recommended that ensemble averaging of traces be conducted across 5-20 gait cycles (strides) [54, 55]. EMG traces are usually chosen and analyzed across a gait cycle or cyclic kinematic events (initial contact, heel strike etc) from synchronized kinetic or kinematics measuring systems [54, 55].

2.8 SEMG amplitude normalization methods

Since raw EMG signal obtained varies across subjects depending on uncontrollable variables such as size, height, skin type, body weight, etc [53]. Normalization of SEMG signal amplitude is essential to remove the effects of the above mentioned uncontrollable variables thus allowing inter-subject and inter-muscular comparisons [64]. Various normalization methods available from existing literature are discussed as follows:

- **Maximum voluntary contraction (MVC):** widely used method, asking subject to initially contract the muscle of interest to the maximum of their ability and using the maximum amplitude value obtained to normalize the test SEMG data [63]. Use of MVC normalization has been criticized for its poor reliability, since it is hard to ensure maximum contraction in the subject especially in the elderly [75].

- **Peak dynamic method:** Dividing each point of the SEMG data by its peak value [75]. Inter subject and within day reliability was noted to be high in peak dynamic method [76].
- **Mean dynamic method:** Dividing each point of the SEMG data in the gait cycle by overall mean value of the gait cycle [75]. Normalizing through mean dynamic and peak dynamic methods has been noted to have less variability than the MVC method [75].
- **Peak to peak amplitude of maximum wave (M-wave) method:** Alpha (α) motor neurons of muscles are externally stimulated and the EMG signal from the muscle is noted, the stimulation current is increased until the M-wave's amplitude does not increase further, this maximum M-wave amplitude will be used to normalize the EMG signal [75].

Based on the previous discussion of normalization methods, peak and mean dynamic methods was noted to exhibit less variability than other techniques, thereby preferred for analyzing gait muscle activity.

2.8.1 Analyzing SEMG data in gait cycle

Surface EMG data analysis methodology of selected frequently cited studies is presented in table 2-2. Clinically relevant information from the SEMG signals can be obtained based on the following approaches.

Table 2-2. Selected SEMG analysis methodology on lower extremity studies.

Author(s)	Muscles compared	Filters	Normalizati on method	Data processing and comparison methodology
Merlo et al.[77]	Rectus femoris, vastus medialis, biceps femoris, semi tendinosus	Bandpass - 3-dB bandwidth: 30–300 Hz; Butterworth 4 th order – cut-off frequency – 10 Hz	NA	Wavelet analysis
Monaco et al. [70]	Peroneus longus, ,gastrocnemius lateralis, soleus, rectus femoris ,vastus medialis, tibialis anterior,, biceps femoris, semitendinosus, adductor longus, tensor fascia latae, gluteus maximus, gluteus medius	Butterworth 4 th order - low-pass -15 Hz	Mean dynamic	EMG profile time interpolated over 200 points. Amplitude and phase comparison of SEMG profiles
Hakkinen et al. [78]	Vastus lateralis, vastus medialis, biceps femoris, quadriceps femoris, rectus femoris	3dB - low-pass -360 Hz	Integrated EMG; isometric MVC; Time normalized.	Comparing integrated EMG as percentage of MVC.
Schmitz et al. [54]	Soleus, gastrocnemius, biceps femoris, medial hamstrings, tibialis anterior, vastus lateralis, rectus femoris.	Butterworth band pass – 6 th order – 10 – 500 Hz; Butterworth low-pass – 6 th order – 6 Hz.	Mean dynamic	EMG data were interpolated to obtain a data series of 1001 points over the gait cycle.
Kang et al. [79]	Vastus lateralis, biceps femoris, gastrocnemius, tibialis anterior	Bandpass filter – 20 – 300 Hz; Notch filter – 60 Hz.	Peak amplitude of gait cycle	Normalized peak amplitude across speeds and activity comparison across percent gait cycle.

Pijnappels et al. [80]	Biceps femoris, rectus femoris, vastus lateralis, tibialis anterior, gastrocnemius medialis, soleus medialis.	Bandpass filter – 10 – 500 Hz;	Maximal activity	Normalized activity compared across stride time. Mean amplitude of gait cycle.
Monaco et al. [81]	Tibialis anterior, gastrocnemius lateralis, rectus femoris, biceps femoris, semitendinosus, tensor fascia latae, adductor longus, gluteus maximus, soleus, gluteus medius.	Butterworth 4 th order - low-pass -15 Hz	Maximal activation	Percent of maximum activation across gait cycle.

Normalization of time in gait SEMG

Time between consecutive heel strikes of the same leg is usually considered as a gait cycle [33, 54, 79]. A gait cycle time period is usually normalized as a percentage of the total gait cycle with first 60% of the gait cycle representing the stance phase and next 40% being the swing phase, the gait cycle is sometimes interpolated into discrete points for comparison [33, 54, 79].

Muscle amplitude comparison

Surface EMG amplitude has been fairly correlated with muscle force, MU firing levels and MUAPS [61-63]. To compare gait-related muscle activity across age groups, normalizing EMG amplitudes and averaging EMG profiles of the gait cycle across 5 to 7 strides are commonly used [19, 27, 43, 56, 57, 82]. Since ensemble averaging of EMG profiles across 5 to 20 strides minimizes variability

and enhances valid representativeness, comparing ensemble normalized amplitude values would indicate relevant differences in terms of muscle force and MUAPs [55]. Amplitude comparison reduces the EMG profile of the entire gait cycle pattern into representative values, this might mask important muscle pattern-based information [63]. However, it is to be noted that amplitude may vary based

Figure 2-13. On/off pattern of lower extremity muscles during a gait cycle (100%). ‘Active’ or ‘on’ states are indicated as blue bars (when muscle amplitude crosses the set threshold value) [8].

on location of the electrodes, hence it is recommended that anatomical landmarks be properly identified and electrodes be placed by the same researcher to minimize variability in electrode locations [54, 83]. EMG values can also be reported or compared in terms of root mean square of amplitude values or as intensity EMG i.e. area under the SEMG amplitude-time curve [54, 83].

SEMG data also enables the researchers to understand, whether the muscle is active during gait cycle or the time of interest. A least threshold value for

activation is assumed or calculated for an individual muscle, if the EMG amplitude cross the threshold then the muscle is considered ‘active’ or ‘on’ [84, 85]. As previously noted, older age groups are known to use different muscle compensatory and synergistic mechanisms [79]. Synergy and co-activation patterns in lower extremity muscle contraction during gait can be analyzed by identifying ‘active’ or ‘on’ periods of a muscle of interest during gait cycle on a time scale (illustrated in figure 2-13) [56, 63, 79, 86]. Signal analysis in the frequency domain is performed to understand pathological condition, fatigue and structural behavioral of muscles [62, 63]. Muscle co-activation analysis based on amplitude depends on the manually set threshold value, this might be a limitation [77]. To overcome this limitation, wavelet transform based algorithms and techniques have been proposed [55, 77, 87].

Integrated SEMG method

Integrated EMG (iEMG) is defined as the area under the curve of the EMG signal, which is calculated as the mathematical integral of the area under the region of interest in the SEMG curve, usually in the stance phase only [88]. The area under the interval is calculated using the Riemann approximation method. It approximates the curve into smaller trapezoids, calculating the sum of area of individual trapezoids and approximating the area. The area under the SEMG curve for stance phase is presumed to represent the energy spent by the muscle for the gait cycle.

2.8.2 Typical reporting of EMG Methodology

Murley et al.'s review article on suggested typical EMG reporting criteria and variables [89].

1. Type of sensors used.
2. Sensor location and placement.
3. Filters, rectification method, sampling frequency and other signal processing/comparison methods.

In the previous sections structural and functional changes in muscle owing to age and resulting conditions like sarcopenia and dynapenia were discussed. In the following sections, review of literature on age-related changes in muscle activity and other patterns during a gait cycle will be discussed. Muscles of interest in the lower extremity will be identified based on their contributions to the gait cycle and literature available on their functional changes with age. Literature on overall changes in muscles' activation and co-activation patterns will also be reviewed. Gaps in existing literature and potential contributions will also be discussed. An anatomical chart of human musculature is enclosed in the appendix 1.1

CHAPTER 3 LITERATURE REVIEW

3.1 Age-related gait functional changes of lower extremity muscles

Literature review on age-related functional changes of lower extremity muscles will be discussed section.

3.1.1 Muscles in the trunk region

Structurally, the thicknesses of trunk muscles (erector spinae, internal oblique and external oblique) was found to be significantly smaller in the older population (mean age - 85.7 year) than the control young (mean age – 20.0 year) [90]. No studies comparing the differences in EMG were found.

During specific tasks like trunk flexion, axial twisting of the trunk and lateral bending of trunk, it was found that erector spinae group, internal oblique and external oblique muscles of the older adults (mean age – 68 years) showed significantly higher values than the young control group (mean age – 21 years), during the axial twist task the older group activated the muscles sooner than the young [91].

3.1.2 Muscles in the hip region

Muscle produces force thereby creating movement of the joint associated with it, this mechanism is usually associated with torque or moment about that joint. Moment is calculated as the product of force and the perpendicular distance from the muscle's insertion to the center of joint [39]. Gait cycle's net extensor torque

magnitude generated by hip muscles was larger in older adults than young adults [92]. Older adult's hip flexor torque during gait cycle was 37% lesser than young adults [92].

Thickness of gluteus maximus, gluteus medius, gluteus minimus and iliopsoas group was smaller in the older adults than young [93]. Mean gluteus medius muscle activation magnitude was significantly higher in older group than young during double support period of stance phase [57]. During gait's double support phase older group activated up to 46% of their maximum capacity compared to 25% in the younger group [57]. Comparing young group, gluteus maximus muscle force (N/Kg) was higher in the older adults in majority of the stance phase [94].

3.1.3 Muscles in the thigh region

Older adults displayed higher mean EMG amplitudes in the beginning of stance phase in biceps femoris and medial hamstrings (semitendinosus and semimembranosus) at faster walking speed than young group (26 ± 3 years), as illustrated in figure 3-1, [54, 84].

Figure 3-1. Medial hamstrings muscle activation difference between healthy older and young adults during gait cycle at various speeds. The horizontal lines above the curve indicated regions of statistically significant difference between age groups [21].

Vastus lateralis mean EMG amplitude of older adults were significantly different from young group during the loading phase of gait as illustrated in figure 3-2 [54]. Reduced quadriceps (Rectus femoris and vastus muscle group) muscle EMG amplitude was reported in older adults [95].

Figure 3-2. Vastus lateralis muscle activation difference between healthy older and young adults during gait cycle at various speeds. The horizontal lines above the curves indicate phases of the gait cycle where average muscle activity differed significantly across [21].

Muscle activity of rectus femoris in old age group was significantly different during loading response and midstance, when compared to young age group (figure 3-3) [54].

Figure 3-3. Rectus femoris muscle activation difference between healthy older and young adults during gait cycle at various speeds. The horizontal lines above the curves indicate phases of the gait cycle where average muscle activity differed significantly across [2].

Older adults showed significantly higher peak EMG amplitudes in vastus lateralis, biceps femoris and gastrocnemius than young adults, as illustrated in figure 3-4 [79].

Figure 3-4. Older adults showed significantly higher peak amplitudes in vastus lateralis, biceps femoris and gastrocnemius. Peak amplitudes normalized (unitless) EMG linear envelopes vs age and speed (PWS - Prefer Walking Speed) [31].

3.1.4 Muscles in the ankle region

In tibialis anterior, peroneus longus, gastrocnemius and soleus significant mean muscle EMG amplitude differences was observed between young and old age group, the differences across various phases is illustrated in figure 3-5 [54, 82, 96].

Figure 3-5. Gastrocnemius and soleus muscle activation difference between healthy older and young adults during gait cycle at various speeds. The horizontal lines above the curves indicate phases of the gait cycle where average muscle activity differed significantly [21].

3.1.5 Speed influences, muscle co-activation, synergy and initiation delay differences in a gait cycle due to aging.

In this section, influence of age on other functional gait muscle activity differences will be discussed.

Influence of speed

Walking speed influences muscle activity during a gait cycle, with increasing walking speed, changes noted are increased muscle activity and change in EMG profile/patterns [54, 84, 97]. Higher EMG amplitudes were correlated high walking speeds [97]. Since faster walking speed needs larger forces for locomotion and support, thereby larger muscle activity maybe recorded.

This aspect might have been overlooked by researchers in the available literature on age-related gait muscle activity differences, the studies may not have considered the effect of walking speed on muscle activity differences [98].

Since, older age group have been reported to walk with slower speeds with reduced step length than young adults i.e. the muscle activity differences observed might have been influenced by slower walking speeds of older adults rather than the effect of age itself [98].

Some studies have tried to address this influence to specifically understand the effect age-speed interaction on gait muscle activity, it was found that speed effects are quite prominent in muscles [54, 84, 97]. But as illustrated in figures 4-1 to 4-5, it can be inferred that though speed-age interaction affected muscle activity, but in

most of the muscle groups age-related differences existed irrespective of the walking speed [54, 79, 99]. Most researchers normalize walking speed using preferred walking speed (PWS) [54, 79, 99]. It has also been reported that across same subjects, SEMG profile and amplitude varied with speed except gastrocnemius muscle activity [79].

Muscle activation times, muscles synergy and co-activation

As noted in chapter 2.1, aging leads to an overall decrease in muscle strength, this may lead to the use of different lower extremity co-activation, synergy and compensatory mechanisms by the older adults unlike the young [39]. Even though speed based differences may be found in the muscle activity, but other aspects of muscle activity like co-activation strategies followed by older group might be different, therefore analyzing co-activation strategies might be useful in understanding age-related muscle activity differences [39]. Analyzing other muscle activity aspects might be important in discerning age-related gait muscle activity differences, in a study it was found that muscle activation strategies during gait can predict propensity to falls in elderly women [86].

During gait initiation the older group, deviated from equal weight bearing between right and left leg than young adults [56]. Tibialis anterior activation duration was shorter in the older subjects than in the stance leg [71]. Late activation onset of gastrocnemius lateralis and soleus (stance leg) in old age group was also observed [71].

Decline of muscle power in the calf muscle and knee extensors in older adults has been noted to be compensated by increased activation or co-activation of other muscles in the lower extremity especially in hip extensors [81, 85, 92, 100].

During stepping tasks, it was found that muscle synergies among older adults were more scattered and combinations of agonist/antagonists occurred more in old group than young at faster walking speeds [70]. Difference in co-activation timing of antagonist muscles involved in gait was also noted [84]. Significant differences were found between the muscle activation strategies between young

Figure 3-6. Muscle activation patterns during stepping task between young and middle-aged adults.

Abbreviations used are st: stance leg, sw: swing leg, ES - erector spinae, MGLU - gluteus medius, BF - biceps femoris, RF - rectus femoris, GA - medial gastrocnemius, TA - tibialis anterior. The vertical lines indicate complete foot-off, initial foot-contact, and complete foot-contact, respectively. Phases A–C refers to the step-initiation, single-leg support, and landing phases. The filled and empty horizontal bars indicate essential (occurrence rate $\geq 90\%$) and non-essential (occurrence rate $< 90\%$) of muscle bursts, respectively. The length of the bar indicates the mean group burst duration. The single cross symbol indicates that the burst was an essential burst in young adults, but not in middle-aged adults. The double cross symbol indicates that the burst was an essential burst in middle-aged adults, but not in young adults [41].

3.2 Effect of footwear features on lower extremity muscle activity

In this section the effect of footwear features on lower extremity muscle activity will be reviewed and discussed.

Footwear features have been widely studied, recommended and used to correct and assist in abnormal, pathological and rehabilitative conditions [23, 28, 102, 103]. Footwear features classified by various researchers are tabulated in table 4-1 and an illustration of typical footwear features is given in figure 3-7.

Figure 3-7. Illustration of various footwear features [12].

Footwear features of clinical interest were identified based various assessment tools and forms used by podiatrists and physiotherapists. The features are tabulated in table 3-2. The identified features will then be individually assessed through literature and isolated further based on their reported effect of muscle activity.

Table 3-1. Footwear features classified by various researchers based on characteristics.

Characteristic	Barton et. al. [102]	Williams [104]	Menz et. al. [105]	Lake [106]
Footwear Style	NA	NA	Boot, clog, sandal, oxford, slipper, mule, moccasin	NA
Fit	Toe-footwear gap, footwear length, footwear width, footwear depth	Vamp, toebox, throat, insole, lining, shank, outersole	NA	NA
Materials	Upper, insole type, outsole type, weight/length ratio	Materials	NA	NA
General structure	Heel height, forefoot height, difference between heel height and forefoot height, last shape, sole attachment type, forefoot sole flexion point, arch support	Heel height	Heel height,	High-cut, low-cut shoes, sole design
Motion control properties	Multiple density sole, fixation (laces, velcro, zips etc.), heel counter stiffness, midfoot sole sagittal stability, midfoot sole frontal stability	Heel density	Shoe fixation, heel counter stiffness, sole rigidity, tread pattern, sole hardness,	Multiple sole density
Cushioning	Lateral midsole hardness, medial midsole hardness, heel sole hardness	NA	NA	Cushioning

3.2.1 Effect of toning footwear types on muscle activity

Toning or rocker bottom footwear (figure 3-8) types have been popular commercially. The shoe construction is primarily characterized by soft or hard rounded soles under the heel area along the anterior-posterior axis acting like an unstable base, this unstable base provides an uneven base for lower extremity muscles to adapt. This is also believed to mimic walking action of barefoot ancestors on uneven surface thereby increase muscle activity and blood flow of lower extremity muscles [107, 108].

Figure 3-8. MBT™ rocker bottom or unstable or toning shoe [1].

It was noted that underutilization of lower extremity muscles especially smaller extrinsic foot muscles during walking could lead to gradual atrophy, loss of strength and force production capacity. It was reported that usage of unstable footwear ensures that all lower extremity muscles including the smaller extrinsic

foot muscles are activated more to balance the body during walking and standing [107, 108].

Rudmann et al. reported that SEMG activity of lower extremity during a gait cycle (when compared with regular sports shoe with normal flat sole), it was found that tibialis anterior intensity decreased by 12.5% during the initial phase of the gait cycle [108]. Increase in muscle activity was also reported in gastrocnemius group, vastus group, rectus femoris, flexor digitorum longus, peroneus longus and semi-tendinosus group [27, 108]. Increased co-contraction between gastrocnemius and tibialis anterior was also observed with rocker bottom shoe type [108]. Nigg et al. noted that an overall increase in EMG muscle activity intensity (IEMG) was compared to the control shoe, tibialis anterior - 70% (SD 85%), gastrocnemius - 38% (SD 41%), vastus medialis - 37% (SD 46%), biceps femoris - 11% (SD 69%) and gluteus medius - 38% (SD 78%). The average overall increase in lower extremity muscle activity was 39% [109]. Large excursion of centre of pressure (COP) both in the anterior-posterior and medio-

Figure 3-9. Center of pressure (COP) excursion differences between unstable and stable soled footwear [12].

lateral direction was reported in unstable shoe and this excursion was correlated with higher muscle activity (Figure 3-9) [109]. This effect was attributed that of the unstable wobble board used in rehabilitation and balance training [27, 109].

Rocker bottom shoes were also noted to improve postural balance, decrease in knee and back pain [13, 110]. In the older subjects, anterior-posterior unstable shoes showed significantly higher muscle activity in vastus lateralis, soleus and tibialis anterior. For biceps femoris muscle, medio-lateral unstable shoes showed the highest muscle activity [110].

3.2.2 Mixed results on the effect of toning exercise footwear on muscle activity

Contrary to some studies claiming increase in muscle activity through toning or unstable sole footwear, there are studies by agencies and other reliable researchers discounting these claims. American Council of Exercise (ACE), America's premier authority on fitness education and certification, conducted an independent research study on three types of toning exercise footwear available on the market. It was found that these toning shoes did not show a significant increase in exercise response or muscle activation in comparison with normal athletic shoe [111, 112].

ACE researchers also criticized majority of the studies supporting the claims of toning shoes to be 'sponsored by manufacturers', 'not peer-reviewed' and 'questionable design' [111]. It was suggested that the unstable design makes the wearer to use slightly different muscle pattern to maintain balance, thus causing

temporary change in muscle loading until our body adapts and thereby no change after that [111].

Horsak et al. have suggested that COP excursion parameters in rocker bottom shoes were not significantly different from other regular sports footwear [113]. No significant differences was found in muscle activity of quadriceps, vastus medialis and lateralis between normal and toning shoes [113]. Unstable shoes may increase activity in smaller intrinsic muscles more than the large muscle groups. since smaller intrinsic muscles like triceps surae play a major role in sensing and responding to joint stability rather than large muscle groups [114].

3.2.3 Multiple density sole and muscle activity

In a multiple density sole, instability is achieved through shape and variable densities of materials used in the sole (as illustrated in figure 3 -10).

Figure 3-10. Illustration of a multiple density sole [10].

In a previous study, Muscle activity was compared between multiple density soled FitFlop™, flip flop and bare foot conditions. When compared with barefoot condition FitFlop™ condition showed a 7%, 8% and 0.2% increase in overall

muscle activity in gluteus maximus, biceps femoris and medial gastrocnemius [115]. The authors did not consider the percentage increase in muscle activity to be significant enough to affect the muscle health, especially in the older population [115].

3.2.4 Heel height and muscle activity

Mika et al. noted that EMG activity (RMS value) of medial gastrocnemius, quadriceps, medial hamstrings and rectus femoris was found to be significantly higher in the high heeled than no heel conditions [116, 117]. The effect was found to be similar in young and middle-aged women [116]. High heeled shoes have been reported to cause knee pain, alter muscle activation and gait patterns [116, 118]. Erector spinae and tibialis anterior muscle activities increased with heel height [117, 118]. In a study by Lee et al. [119], high heels were correlated with decrease in gastrocnemius muscle SEMG activity.

Negative heeled shoes (heel height is lower than toes) showed increase in gait muscle activity of tibialis anterior, lateral gastrocnemius and biceps femoris muscle [120]. Negative heeled shoes were noted to place higher demand on lower extremity muscles [120].

3.2.5 Minimalist shoes and muscle activity

Use of minimalist shoes is gaining popularity recently with Adidas™ ‘Feet you wear’, Nike™ ‘Free shoes’ etc. Kinetic and kinematics have been noted to change during barefoot running when compared with shod running [114]. Barefoot

training in athletes have been noted to improve strength in tibialis anterior, biceps femoris, gastrocnemius, soleus and peroneus longus [114]. Low frequency of running related injuries like osteoarthritis, stress fractures etc. have been reported in barefoot runners than shod runners [121, 122]. EMG activity peaks of vastus lateralis and gastrocnemius were noted to occur early in normal shoe condition compared with minimalist shoe running [89].

An exclusive study by the American Council of Exercise (ACE) pointed out that though barefoot shoes encourage optimal forefoot strike in the half of the subjects involved in the study, rest half continued their heel strike pattern even in barefoot shoes, this when combined with non-padding of minimalist shoes may increase risk of injury than minimizing it [123].

3.2.6 Insole and muscle activity

In the following sections, the effect of foot orthoses and insoles on muscle activity will be discussed.

Insole texture

It was found that textured shoe insole insert (compared to smooth sole insole insert) exhibited a reduction in intensity of soleus EMG signal, a significant 13% during propulsive phase of the stance [124]. A 13 % decrease in the total energy of tibialis anterior and significant overall decrease in the rectus femoris energy

was also observed while using textured insole [124]. Since aging is correlated with loss of cutaneous insensitivity affecting afferent feedback for balance and locomotion, having a textured insole might stimulate nerve activity and change gait patterns [124, 125].

Insole material

Ogon et al. compared the effect of hard sole made from semi-rigid shock absorbing material (PE Lite) and soft sole made of shock absorbing material (PPT) on spine musculature, a delayed difference between heel strike and spine muscle activity onset response was observed between conditions, soft material insoles showed the slowest response, thus indication of shock absorption capacity in soft material soles [126]. Insole made of Ethyl Vinyl Acetate and Polyurethane were noted to exhibit significantly different gastrocnemius muscle activity patterns [127]. Soles designed to absorb shock and increase the force of restitution were noted to reduce fatigue in lower extremity muscles [128]. Higher (EMG RMS value) vastus medialis pre-activation occurred in viscoelastic sole than soft elastic sole [129].

Foot orthoses, shoe inserts and muscle activity

Different foot orthoses and shoe inserts have been prescribed and used to treat various health conditions. Wearing foot orthoses reportedly changes skeletal alignment while walking thereby change in skeletal loading and muscle activity

patterns [130, 131]. Orthoses with thick medial, rearfoot and forefoot areas had significantly higher EMG intensity in tibialis anterior, gastrocnemius medialis, peroneus longus and biceps femoris [130]. In a 2009 review by Murely et. al. [131], it was reported that nearly all studies on effect of foot orthoses on lower limb muscle activity focused on young adults only.

Tomrao et al. noted that the effect of foot orthotics on muscle activity of tibialis anterior, peroneus longus and gastrocnemius was not significantly different in amplitude when compared with no orthotic condition [132]. Lateral wedge insoles have been reported to reduce the knee varus torque , thus recommended in managing osteoarthritis [133]. Effect of the angle of wedging (0°, 15°, 30°) produced significantly higher EMG values in tibialis anterior and peroneus longus compared with barefoot walking. There was also significant difference between the angle of wedging (0°, 15°, 30°) on muscle activity [134].

3.2.7 Other footwear features noted to affect muscle activity

Wedging of midsole (neutral, varus and valgus) was noted to have effect on muscle forces of extensor digitorum longus, peroneals, tibialis anterior and posterior [135]. Military boots with hard inflexible soles were noted to produce higher activity in tibialis anterior and rectus femoris than conventional running shoes [136]. Sole stiffness was noted to affect EMG profiles of soleus, gastrocnemius medialis, tibialis anterior and peroneus longus [137].

Further modifications suggested Ann et al. on conventional running shoes were inducing medio-lateral instability on the shoes (MLI) by shaving the mid- and outsole material on the medial and lateral sides creating instability in the medio-lateral direction [11]. The second modification on anterior posterior instability (API) is done by adding foam with hardness 40-50 shore and a rocker radius of 50cm creating instability in the posterior to anterior direction [11].

3.2.8 Components of exercise footwear design

Walking exercise footwear are generally light weight with shock absorber soles [138, 139]. Primary components of footwear design considered in the literature [138-140] are categorized as follows

- Forefoot - components cover and protect the feet from external hazards
 - Vamp - Covers toe and forefoot, usually made of continuous piece of material
 - Quarter - Covers midfoot and heel regions
- Lower -provides cushioning, ground impact strength and grip
 - Insole
 - Outsole
 - Midsole
 - Method of attaching midsole and outsole
 - Shank and heel
 - Flexion point of the shoe etc

- Shape of the last– responsible for fit and comfort of the shoe
 - Height of the toe box
 - Instep height
 - Heel width
 - Ball width
 - Ball to heel width ratio
 - Overall length and girth of the last
 - Curvature profile of the last bottom etc.
- Other components
 - Shoe counter
 - Permeability to air and moisture
 - Torsional flexibility

3.3 Summary

Age-related functional leg muscle activity differences existed during gait cycle between young and old adults, though trunk muscles' contributions to gait cycle's vertical ground reaction force was significant, but studies on age-related gait cycle muscle activity differences on them were not found in the existing literature [37]. Age-related differences were more prominent at faster walking speeds than slower and preferred walking speeds, EMG amplitudes were also higher at faster walking speeds [54]. However, certain muscle activity differences existed across age groups irrespective of walking speeds [54]. Lower extremity muscle co-activation and synergy mechanisms were noted to be different across age-groups [101].

Studies on age-related lower extremity muscle activity differences have mostly focused on one muscle group or few muscles out of major lower extremity muscles contributing to the gait cycle [37, 54, 84, 96]. Structurally, muscle peaks and weakens from the fourth decade of life (middle-aged), however studies designed to understand age-related differences have primarily included subjects of young (20 – 25 years) and older adults (60+ years) but have failed to consider middle-aged groups.

Among the footwear features studied by previous researchers, sole's shape, height and density were the most prominently to affect gait muscle activity, but studies have focused primarily on younger or middle-aged adults. Barefoot style shoes are popular, but could make users susceptible to injuries. Insole and midsole's shape, hardness and material were also noted to have some effect on lower extremity muscle activity.

In a footwear, midsole and outsole based footwear features have been reported to affect lower extremity muscle activity patterns during gait [1-5]. But, a close scrutiny on existing scientific evidence highlights inconsistency in the surface electromyography (SEMG) criteria and statistical protocols considered to infer the features' effect on muscles [1-5]. Effects of popular 'muscle toning' exercise footwear types have also been concluded by some studies including the one commissioned by American Council on Exercise, to be insignificant to be concluded as effective.

The EMG methodology routinely involved averaging of the muscle activity across all subjects or a muscle or an age-group into one representative dataset. Then, comparing, analyzing and drawing conclusions based on the representative dataset [13-17]. This could lead to highly variable results that could be inferred in various ways.

CHAPTER 4 METHODOLOGY

In this chapter Hypotheses will be formulated based on the objectives of the literature review. Experimental methodology and procedures to test the hypotheses will be discussed.

4.1 Formulation of hypothesis

Age-related differences in gait muscle activity pattern exists irrespective of walking speed differences with age. Structurally, muscle peaks and weakens from the fourth decade of life (middle-age), it was noted that studies on age-related gait muscle activity differences have mainly focused on young (20 – 30 years) and older adults (65+ years) but have failed to consider middle-age groups, though it was noted to be a period for key structural and functional muscle change. Exercise intervention during middle-age may slow down deterioration of muscle health.

Footwear features, such as midsole and outsole modifications etc, have been noted to affect gait kinetics, kinematics and muscle activity. Hence, it can be inferred that certain footwear features especially the geometry and shape of the sole could positively influence gait patterns during walking exercise and enable the wearer to exercise his/her lower limb muscles optimally.

Muscle toning shoes like Sketchers Shape-Ups, MBT (Masai Barefoot Technology) and Reebok EasyTone etc are popular shoes available in the market. But according to various researchers and a study conducted by American Council on Exercise (ACE) scientific evidence for existing toning footwear types that

claim to provide lower limb exercises, it was found that the claims weren't scientifically accurate as claimed by researchers supporting toning footwear's effectiveness. ACE also stated that studies purported to support these muscle toning footwear were biased and inconclusive.

Generally, the studies designed to validate the above footwear features focused only the overall increase in the muscle activity between subjects wearing the specified type of shoe and a normal control shoe. Most of the footwear feature studies has been primarily on the young population, middle-aged population or one particular muscle group. But for older adults, a mere increase in mean muscle activity or intensity of one muscle or one functional muscle group cannot be comprehensively considered as improvement in the overall muscle health. As noted in the previous sections musculature in older adults are structurally and functionally different. Old age groups also employ co-activation and compensatory mechanisms i.e. a specific increase muscle activity one region might cause an undesirable decrease or increase in activity of another muscle group. For a comprehensive study on the effect of footwear features on lower extremity muscle health, the effect of these compensatory mechanisms has to be considered along with overall increase in muscle activity.

This project's exercise footwear feature identification approach aims to directly target and improve the muscle deterioration happening as a function of age. To achieve this, a normative and quantified approach would be taken by quantifying

the gait muscle activity and compensatory differences between young (20 – 30 years), middle-aged (40 – 60 years) and older adults (65+ years).

Footwear sole features aiming to address age-related differences by enabling higher muscle in will be identified and isolated. Inconsistencies and differences on results obtained will be analyzed through various SEMG comparison procedures including Amplitude versus IEMG technique, intra-subject versus inter-subject differences

Therefore, the objective of the project is to identify exercise footwear features that improve lower extremity gait muscle activity in middle-aged and older adults through amplitude and integrated surface electromyography method.

4.2 Hypotheses to be tested

Based on the project's objectives, the following set of hypotheses will be investigated

Based on literature review, the following hypotheses were made

- Hypothesis 1: Presence of a leg-dominance effect in lower extremity muscle activity.
- Hypothesis 2: age-related differences can be observed in the lower-extremity gait muscle activity among young, middle-aged and older adults.
- Hypothesis 3: Midsole and outsole footwear features affect lower-extremity muscle activity differently across age-groups.

- Hypothesis 4: Different SEMG data analysis methodologies have varied effect on the results obtained: Amplitude analysis versus Integrated EMG analysis, Intra-subject versus Inter-subject differences.

Considering the objectives and hypotheses following experimental methodology will be applied

For experimentally quantifying age-related muscle activity differences and isolating the effect of footwear features on lower extremity gait muscle activity, surface EMG based methodology was chosen as the primary measurement medium.

Experimental procedures involving human subjects, risk assessment, safety precautions and consent forms for subjects have been approved by university's ethics Institutional Review Board (IRB).

Various conditions to be compared on SEMG of ten-lower extremity muscles via hypothesis are illustrated as follows. The conditions were compared across the same verticals.

<u>Hypothesis</u> <u>1:</u> <u>Dominance</u> <u>-conditions</u> Dominant leg vs Non- dominant leg	<u>Hypothesis</u> <u>2:</u> <u>Age-groups</u> Young vs Middle- aged vs Older adults	<u>Hypothesis</u> <u>3:</u> <u>Footwear</u> <u>conditions</u> Multiple density vs Rocker bottom vs Minimalist	<u>Hypothesis</u> <u>4:</u> <u>Subject</u> <u>variability-</u> <u>conditions</u> Intrasubject vs Intersubject	<u>Hypothesis</u> <u>4:</u> <u>SEMG</u> <u>conditions</u> Amplitude vs Integrated – SEMG (IEMG)
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4.3 Subjects

To quantify age-related effects on lower extremity gait muscle activity, studies will be conducted involving one or all the following three groups of healthy male subjects

1. Young subjects aged 20 to 30 years. (Age: 24.6 (SD:0.89) yrs, Height: 173.6 (SD: 8.08), Weight: 70.2 (SD:12.70) kg)
2. Middle-aged subjects aged 40 to 60 years. (Age: 55.4 (SD:2.61) yrs, Height: 170.8 (SD:5.97) yrs, Weight: 65.6 (SD: 11.61) kg)
3. Older subjects aged 65+ years. (Age: 67.6 (SD: 5.22) yrs, Height: 172.0 (SD: 2.35) cm, Weight: 66.8 (SD:7.26) kg)

Overall, Fifteen subjects with Age: 49 ± 19 yrs, Height: 172 ± 6 cm, Weight: 68 ± 10 kg. Structurally, muscle peaks and weakens from the fourth decade of life, based on literature review, it was found that studies designed to understand age-related differences have primarily included subjects of young subjects and older subjects but have failed to consider middle-aged groups. Body weight and height of the subjects was controlled for each age group. Since the protocol requires placement of SEMG electrode sites close to private parts, male subjects were used. Based on the statistical power inference drawn by Nigg et al. for a EMG based footwear study, it was concluded based on a priori power analysis on EMG intensity five subjects were sufficient to demonstrate “a minimum 10% change from control condition to gain statistical significance at a 95% confidence level” [109].

4.4 Consent and subject exclusion criteria

Standard SEMG protocols on lower extremity muscles involve placing of SEMG electrodes on the surface of the skin close to private parts in the pelvic and thigh region. The procedures also would involve skin preparation including shaving of hair and cleaning the skin. Hence, healthy male subjects are preferred. Since it involved human subjects, permission from University's institutional review board was obtained for the protocol and consent seeking criteria.

Initially, subjects will be briefed about the protocol, risk involved, safety precautions and an informed consent will be obtained. Subjects will also be debriefed after the trials.

Subjects with skin infections, pathological or abnormal conditions like osteoarthritis, joint pain, muscle trauma, sprains, muscle tear, neural conditions affecting gait muscle activity patterns, etc., were excluded from the study.

Screening for the above pathological and abnormal conditions will be done through a simple interview asking relevant questions and a visual inspection through a sample walking trial Dynamic Gait Index (DGI) scoring methodology and scale would be used as a predictor for falling during older and middle-aged gait, subjects scoring below 19 in the DGI scale were excluded from the study [54].

4.5 Measurement system setup

A general measurement setup for the experiments in this project shall include the following variables and relevant measurement systems.

- **Muscle activity variable** - Sixteen channel wireless EMG system paired with footswitches to measure muscle activation variables.
- **Heel-strike calculation** – Pressure based foot-switches.

An adopted (from Frigo et al. [55]) schematic illustration of a typical SEMG based gait analysis setup with a TV-based motion analyzer similar to the current experimental setup is shown in figure 4-1.

Figure 4-1. An adopted illustration of the instrumentation used in the SEMG experimental setup.
Image source -[49].

4.6 Materials required

The equipment used for conducting the trials to validate the protocol is Mega Electronics Wireless Bio-Amplifier (WBA) system which is shown in Figure 4-2, 4-3 and 4-4. Other materials such as razors, alcohol wipes, and micro-pore first aid tape were also used in this experiment.

Figure 4-2. Mega Electronics WBA system with 16 channels capability. Includes receiver, sensors, charging docks and footswitch.

Figure 4-3. WBA sensor with 3 colour codes: Black (ground), Red (+), Yellow (-).

Figure 4-4. WBA sensors with electrodes to be attached to skin

Figure 4-5. Schematic Setup of WBA.

The workstation (laptop) is installed with MEGAWIN, a program that captures the raw data from the sensors. MEGAWIN is equipped with data processing capability such as RMS smooth that can replace low band pass filter and full-wave rectification that are usually required in raw data processing[141].

4.7 Experimental Method

Based on the hypotheses, it can be found that gait muscle activity variables are of primary interest.

A general SEMG testing protocol and statistical comparison methodology will be followed for all the hypotheses to be tested with slight variation in comparison conditions. These methods are discussed in the following sections.

4.7.1 SEMG methods

It can be inferred from the literature review that, owing to high frequency content inherent in an SEMG signal might lead to high variability across sessions. Among factors indicated in figure 2.12 and in accordance with previous SEMG studies [15-18] SENIAM (Surface Electromyography for the non-invasive assessment of muscles) standards were followed. SENIAM is a European concerted action in the Biomedical Health and Research Program (BIOMED II) of the European Union. Following recommendations from SENIAM would enable minimization of variability in SEMG Signals [1].

1. Electrode placement, skin preparation and site identification.
2. Choice of hardware and signal processing techniques.
3. Standard experiment/statistical protocol across subjects and amplitude based normalization techniques.

A sixteen channel differential electrode wireless EMG system will be used to measure SEMG signals from the following muscles: soleus (SOL), gastrocnemius medialis (GM), gastrocnemius lateralis (GL), tibialis anterior (TA), peroneus longus (PL), vastus lateralis (VL), vastus medialis (VM), rectus femoris (RF), semitendinosus/mebranosus (SM), biceps femoris (BF), gluteus maximus (GM), gluteus medius (GME) and tensor fascia latae (TFL).

Owing to the location of GM, GME and TFL being close to private parts, subject's approval will be specifically sought before placing electrodes in the relevant regions.

Electrode site identification and skin preparation

Since the EMG signal is directly affected by the selection of electrode sites and skin preparation, site identification and skin preparation will be done by the same investigator. Subject positioning, skin preparation and site identification shall be done considering SENIAM's (surface EMG for non-invasive assessment of muscles) recommendations and clinical inputs from Singapore General Hospital. [142, 143]. Protocol for electrode site identification based on anatomical landmarks and muscle palpation tests is described in table 4-1

Table 4-1. Lower extremity muscles' electrode site location (indicated by circle) and functional tests for muscle palpation. Illustrations have been adopted from SENIAM's website and Konrad's SEMG teaching manual on EMG [57, 140].

Muscle	Function of the muscle	Electrode site location	Muscle palpation test	Electrode site illustration
Soleus	Plantarflexion and ankle inversion	Below the gastrocnemius muscle. Placement medial or lateral to the Achilles tendon	Dorsiflexion against manual resistance.

Gastrocnemius	Plantarflexion and knee flexion	Placement on the posterior portion of the leg about one-third of the distance from the knee and Achilles tendon. Medial and lateral sites positioning along the midline	Plantarflexion against manual resistance.
Tibialis anterior	Ankle dorsiflexion	Placement on the lateral side of the medial shaft of the tibia, at a one-third of a distance from knee to the ankle.	Dorsiflexion in a seated position against resistance
Peroneus longus	Ankle inversion and plantar flexion of the foot	Placement about one-third of the distance from the fibular head to the foot	Ankle inversion against manual resistance or fanning out of ankle
Semitedinosus & Semimembranosus	Knee flexion, lateral -medial rotation and extension of the hip	Medial side placement at half the distance between gluteal fold and back of knee	Subject in prone position and flexing knee against resistance.

Biceps femoris	Knee flexion, lateral - medial rotation and extension of the hip.	Lateral side placement at half the distance between gluteal fold and back of knee	Subject in prone position and flexing knee against resistance.
Vastus lateralis	Knee extension	Electrode placement at the distance of 3- 5 cm above the patella head at an oblique angle to the thigh midline	Knee extension against resistance in a seated position.
Vastus medialis	Knee extension	Placement 2cm medially from the superior rim of the patella and by moving through an oblique angle of 55 degrees.	Knee extension against in a seated position
Rectus femoris	Knee extension and hip flexion	Midway between iliac crest and the knee	Extending knee against resistance in a seated position

Tensor fasciae latae	Hip rotation, knee extension and medial rotation	Electrode placement at one-third of a distance from the iliac crest to the knee joint, immediately below the anterior superior iliac spine of the iliac crest	Abduction of leg with internal hip rotation against resistance	
Gluteus maximus	Helps in hip extension and lateral rotation	The electrode is placed about 1- 2 inches above the gluteal fold.	External rotation of the thigh against resistance	
Gluteus medius	Helps in hip extension and stabilization	Placement at one-third of a distance of the iliac crest to the trochanter	Abduction against resistance	

Skin preparation

After identification of ideal electrode placement site based on anatomical landmarks and muscle palpation test, the site will be marked with a marker. The site was then shaved and cleaned with alcohol in accordance with SENIAM standards for skin preparation, until mild redness occurs. After cleaning the

Figure 4-6. Left - Skin after shaving and cleaned with alcohol with mild redness for tibialis anterior site. Right – Electrode fixation on left and right tibialis anterior muscle after skin preparation.

shaved area, the electrodes will be fixed firmly to the skin with aid of tapes or other means that would prevent motion artifacts, as illustrated in figure 4-6. Acquisition of raw EMG data can begin after skin preparation.

SEMG Signal acquisition, processing and statistical comparison

Raw EMG signal acquired is a combination of noise and other artefacts; the signal has to be processed/filtered to obtain relevant and valid muscle activity information. The step by step but overall signal processing procedure for gait cycle in the current project is illustrated as a flow chart in Figure 4-7. Individual steps will have modified based on the

Figure 4-7. SEMG data processing protocol

The signal processing will be conducted as per the SENIAM and ISEK (International Society of Electrophysiology and Kinesiology) standards [142, 144]. The signal shall be processed using EMG Works Analysis™ Delsys, MATLAB (Mathworks™) (programming code enclosed in appendix 1.3) and Microsoft EXCEL™. The raw SEMG signal will be filtered through a sixth-order Butterworth band-pass filter with corner frequency of 10 – 500 Hz [54] to eliminate artifacts, crosstalk and other noises which are usually of extreme low and high spatial frequency. The filtered data will then be full-wave rectified to convert negative voltage values to positive. To create a linear envelope, the rectified data will be subsequently passed through a Butter-worth low pass filter with corner frequency of 6 Hz, a sample illustration of linear envelope gastrocnemius muscle activity is shown in figure 4-8. After linear envelope creation, gait cycle identification and isolation will be done via synchronized footswitches. Sample gait cycle muscle activity profile of gastrocnemius muscle is illustrated in figure 4-9.

Figure 4-8. Sample illustration of linear envelope of gastrocnemius SEMG data.

Figure 4-9. Sample muscle activity profile of gastrocnemius muscle during gait cycle.

Normalization of processed SEMG data is done to facilitate comparison across subjects [145-147]. The mean voltage of SEMG curve of a gait cycle is identified and the curve is normalized based on the mean amplitude (voltage) value of the gait cycle, as indicated by the equation 4.1.

$$(4.1) \quad |V| = \frac{\text{Voltage (V)}}{\text{Mean voltage}}$$

A sample illustration of normalized SEMG linear envelope of gait cycle is

illustrated in figure 4-10.

After normalization, SEMG profile may be shifted and matched with occurrence of peak across same subjects to enhance accuracy of amplitude measurement. The normalized data was then interpolated to obtain a series of 100 points for respective gait cycles and processed to represent the curve in terms of percentage of the gait cycle. Ensembled average of SEMG normalized gait cycle of a muscle across five trials will be considered for statistical analysis (sample illustrated in figure 4 - 11), for age groups gait cycle SEMG profiles will be averaged.

Figure 4-10. SEMG Profile of gastrocnemius muscle expressed as percentage of gait cycle.

The above proposed methodology aims to represent SEMG in the form of ensemble average and compare aspects like amplitude, intensity etc. Though the methodology captures the averaged general SEMG profile across subjects, this averaging cancels out any individual differences in SEMG activity across subjects, this is a potential limitation for this proposed methodology.

Upon the completion of ensemble averaging, the data is divided into different phases in the gait cycle such as loading (0 – 10%) of the gait cycle, mid-stance (10 – 30%), terminal stance and pre-swing (30 – 60%), initial swing (60 – 73%), and terminal swing (87 – 100%). The division of the gait cycle phases were based on a previous SEMG comparison methodology done by Schmitz et al [21]. The normalized SEMG amplitude (dividing each point of the SEMG data in the gait cycle by overall mean amplitude value of the gait cycle) of the exercise footwear conditions will be statistically compared (student's t-test) along the same gait cycle phases against control shoe condition across the same age group.

Statistical analysis and comparison

The SEMG curve and data acquired from the previously discussed signal processing protocol will be divided into 20 or more discrete equal intervals or different phases along 100 % of gait cycle linear envelope. Mean amplitude $\pm$ SD values and area of SEMG gait cycle curve calculated through the trapezoid method along the divided interval or phase will be used for comparison. Student's t-test will be used to verify statistical significance ($p\text{-value} < 0.05$) for comparison and interaction of factors. T-test will also be used to analyse effect of age (young, middle-aged, older) and conditions (multiple density, minimalist, rocker bottom, and normal control condition refer figure 4.12). For inter-subject comparison SEMG curve for all subjects across a particular condition was averaged in to one representative dataset. For intra-subject comparison, footwear conditions were

compared across trials along a same subject. All results are indicated in appendix

1.3

Figure 4-11. Illustration of modifiable insole, midsole and outsole features on a footwear [5].

CHAPTER 5 RESULTS

5.1 Hypothesis 1: Comparison of a leg-dominance in lower extremity muscle activity

Comparison of lower extremity muscle activities between the left (mostly non-dominant) and right (mostly dominant) leg was conducted to validate the previously established SEMG methodology to avoid leg dominance effect as a confounding effect [148, 149] and validate the experimental protocol designed for measuring the hypothesis. It was hypothesized that muscle activities during the gait cycle will be significantly different between the dominant and non-dominant leg.

The hypothesis test was conducted on five young male subjects as per previous established theory and protocols. To identify the gait cycle, gastrocnemius muscle activity was used due to its distinct ‘on’ and ‘off’ SEMG pattern. It was established previously [79] that gastrocnemius muscle activity does not significantly vary with walking speed and the across-subject SEMG profile variability was minimal among all lower extremity muscles. Mean normalized muscle activity $|V|$ across five equal discrete intervals along a gait cycle was compared between dominant and non-dominant leg. All five subjects showed dominance effect i.e. overall high mean normalized muscle activity in the dominant leg, as illustrated in figure 5-1. Student’s t-test comparison between the legs for five subjects revealed the existence of a dominant leg ($p < 0.05$) this is in accordance with results reported by Arsenault et al., Chatinier and Rozendel and

Singh, on gait bilateralism of EMG profile, it was stated that the lower limbs are not used equally in gait [57-59]. The difference in EMG profile between the legs during walking can be explained by the dissimilarity occurring during gait in the spatio-temporal and kinematic parameters such as stride length step length, angle of foot placement and knee flexion between the limbs [60, 61]. Since the subjects were young and healthy between 20 – 27 years, asymmetry can also be attributed to the possible difference in the duration of initial and terminal support period [62, 63]. The calculated mean value across all five subjects, revealed right legged dominance. This occurs in 90% of individuals with left-sided cerebral hemispheric dominance [64, 65], since the left cerebral hemisphere controls the movements in the right side of the body.

Students t-test comparison of the mean gait muscle activity for each of the thirteen lower extremity muscles for all subjects during all key phases of gait cycle showed a significant difference between both the legs however, certain muscles during specific phases of the gait cycle showed no difference ($p > 0.05$) in both the legs. The gastrocnemius medialis and vastus lateralis of one of the subject showed no difference between the legs during initial stance and pre-swing conditions. Another subject showed no dominance in the initial and pre-swing conditions in the gastrocnemius lateralis muscle. Another subject showed no difference in muscle activity during the mid-stance in the vastus medialis muscle.

The lack of dominance during particular gait phases can be due to the similar muscle activation and muscle efficiency between both the legs during that specific

phase [66]. The above observations can also be attributed to the fact that leg preference is associated with the task being performed [67] and this is accordance to the Previc's neurodevelopmental theory that there is no clear dominant leg in the bilateral setting [68]. He had explained that postural support is provided by one leg while the movement required in gait is provided by the other leg and this function can be provided by either left or right leg hence, the presence of dominance is unclear. Thus confirming the hypothesis.

Figure 5-1. Sample mean gastrocnemius medialis muscle activity for the left and right leg of a subject.

Details of gait muscle activity comparison (Student's t-test) across individual lower extremity muscles is tabulated in table 5-1.

Table 5-1. Significance of muscle activity amplitude differences on mean normalized EMG between dominant vs non-dominant leg (n = 5).

Phase of the gait cycle	Muscle	p – value of muscle activity amplitude differences between dominant vs non-dominant leg
Loading Response (0-10%)	Soleus	< 0.05
	Gastrocnemius medialis	< 0.05
	Gastrocnemius lateralis	< 0.05
	Peroneus longus	< 0.05
	Tibialis anterior	< 0.05
	Vastus lateralis	< 0.05
	Vastus medialis	< 0.05
	Rectus femoris	< 0.05
	Semitendinosus/membranosus	< 0.05
	Biceps femoris	< 0.05
Mid-stance (10-30%)	Soleus	< 0.05
	Gastrocnemius medialis	< 0.05
	Gastrocnemius lateralis	< 0.05
	Peroneus longus	< 0.05
	Tibialis anterior	< 0.05
	Vastus lateralis	< 0.05
	Vastus medialis	< 0.05
	Rectus femoris	< 0.05
	Semitendinosus/membranosus	< 0.05
	Biceps femoris	< 0.05
Terminal stance and pre-swing (30 – 60%)	Soleus	< 0.05
	Gastrocnemius medialis	< 0.05 (no significant difference was noted in one of the subjects)
	Gastrocnemius lateralis	< 0.05 (no significant difference was noted in one of the subjects)
	Peroneus longus	< 0.05
	Tibialis anterior	< 0.05
	Vastus lateralis	< 0.05
	Vastus medialis	< 0.05 (no significant difference was noted in one of the subjects)
	Rectus femoris	< 0.05
	Semitendinosus/membranosus	< 0.05
	Biceps femoris	< 0.05

Pre and Initial Swing (50 – 73%)	Soleus	< 0.05
	Gastrocnemius medialis	< 0.05
	Gastrocnemius lateralis	< 0.05
	Peroneus longus	< 0.05
	Tibialis anterior	< 0.05
	Vastus lateralis	< 0.05
	Vastus medialis	< 0.05
	Rectus femoris	< 0.05
	Semitendinosus/membranosus	< 0.05
	Biceps femoris	< 0.05
Terminal Swing (87 – 100%)	Soleus	< 0.05
	Gastrocnemius medialis	< 0.05
	Gastrocnemius lateralis	< 0.05
	Peroneus longus	< 0.05
	Tibialis anterior	< 0.05
	Vastus lateralis	< 0.05
	Vastus medialis	< 0.05
	Rectus femoris	< 0.05
	Semitendinosus/membranosus	< 0.05
	Biceps femoris	< 0.05

5.2 Preliminary test: Comparison of muscle activity between barefoot and shod conditions on young subjects

To confirm effect of footwear feature on muscle activity, a preliminary test (as per previously described SEMG protocol in chapter 4) was conducted on five young male subjects comparing barefoot and shod condition on the dominant leg. It was hypothesized that muscle activity would be different between barefoot and shod condition on dominant leg. Comparison of the mean muscle activity between barefoot and shod conditions across five equal discrete intervals across gait cycle showed that subjects generally exhibited greater muscle activity in barefoot rather than shod condition across lower extremity muscles: Soleus, gastrocnemius medialis, gastrocnemius lateralis, tibialis anterior, peroneus longus, vastus

lateralis, vastus medialis, rectus femoris, semitendinosus/membranosus and biceps femoris (a sample SEMG profile comparison is illustrated in figure 5-2) showed significant difference between the barefoot and shoed conditions, thus adding strength to the project's hypothesis about footwear feature influencing muscle activity.

Figure 5-2. Sample mean gastrocnemius medialis muscle activity for the barefoot and shoed condition for one of the young subjects.

5.3 Hypothesis 2 and 3: age-related difference and effect of footwear features

The following hypothesis 2 and 3 were Interconnected and hence will be tested together

- Hypothesis 2: age-related differences can be observed in the lower-extremity gait muscle activity among young, middle-aged and older adults.
- Hypothesis 3: Midsole and outsole footwear features affect lower-extremity muscle activity differently across age-groups.

Four different footwear features were tested on the three age-groups as stated in chapter four. They are the minimalist shoe (Adidas Adipure Trainer 1.1™), multiple density sole (FitFlop™), rocker bottom (MBT™) against a normal control flat-soled canvas footwear (North-star™) with minimal features as a control shoe (Figure 5.3).

Figure 5-3. Adidas Adipure Trainer 1.1, FitFlop, MBT, North star (from left to right).

Adidas Adipure Trainer will be the minimalist shoe in the experiment, FitFlop will be the multiple densities shoe, MBT will be the rocker-bottom toning shoe and lastly the North-star will be the control shoe.

Based on the testing protocol, experiments were done on subjects of 3 different age groups as described in section and the results were tabulated in this section. T-test is conducted to verify the significance of difference between the shoes types with reference to the control shoe. A P-value of 0.05 is set to validate the statistical differences ($P < 0.05$) between the different footwear and the control shoe. The area under SEMG or Integrated SEMG and normalized muscle activity of amplitude were compared. Studies will be conducted involving one or all the following three groups of healthy male subjects. Inter-subject based comparison on

4. Young subjects aged 20 to 30 years
5. Middle-aged subjects aged 40 to 60 years
6. Older subjects aged 65+ years.

Overall, Fifteen subjects with Age: 49 ± 19 yrs, Height: 172 ± 6 cm, Weight: 68 ± 10 kg. The subjects were requested to perform 10 walking trails of 5-meter distance at their preferred walking speed on each footwear condition and control footwear. Upon the completion of ensemble averaging, the data is divided into different phases in the gait cycle such as loading (0 – 10%) of the gait cycle, mid-stance (10 – 30%), terminal stance and pre-swing (30 – 60%), initial swing (60 – 73%), and terminal swing (87 – 100%). The division of the gait cycle phases were based on a previous SEMG comparison methodology done by Schmitz et al [6]. The normalized SEMG amplitude (dividing each point of the SEMG data in the gait cycle by overall mean amplitude value of the gait cycle) of the exercise

footwear conditions will be statistically compared (student's t-test) along the same gait cycle phases against control shoe condition across the same age group.

5.3.1 Minimalist sole type

In this section, the P-value for comparison between young and middle-aged, young and older adults, and middle-aged and older adults for four shoe conditions. The results for all the above conditions are tabulated from Table 5.2 to 5.5. The “*” sign symbolizes statistical differences ($P < 0.05$) for the phase.

Table 5-2. P value for the comparison of normalized amplitude between young and middle-aged in minimalist shoes

Muscle	P value				
	Loading phase (0-10%)	Mid-stance (10%-30%)	Terminal stance and pre-swing (30%-60%)	Initial swing (60%-73%)	Terminal Swing (87%-100%)
Soleus	< 0.05	>0.05	<0.05	>0.05	<0.05
Gastrocnemius medialis	< 0.05	<0.05	<0.05	<0.05	<0.05
Gastrocnemius lateralis	> 0.05	<0.05	<0.05	<0.05	<0.05
Tibialis anterior	< 0.05	<0.05	<0.05	<0.05	>0.05
Peroneus longus	< 0.05	<0.05	<0.05	<0.05	<0.05
Vastuslateralis	< 0.05	>0.05	<0.05	<0.05	>0.05
Vastusmedialis	> 0.05	>0.05	<0.05	>0.05	<0.05
Rectus femoris	< 0.05	>0.05	<0.05	>0.05	>0.05
Semitendinous/mebranosus	< 0.05	>0.05	>0.05	<0.05	>0.05
Biceps femoris	< 0.05	<0.05	>0.05	<0.05	<0.05

Table 5-3. P value for the comparison of normalized amplitude between young and older adults in minimalist shoes

Muscle	Loading phase (0-10%)	Mid-stance (10%-30%)	Terminal stance and pre-swing (30%-60%)	Initial swing (60%-73%)	Terminal Swing (87%-100%)
Soleus	<0.05	>0.05	<0.05	>0.05	<0.05
Gastrocnemius medialis	>0.05	<0.05	<0.05	<0.05	<0.05
Gastrocnemius lateralis	<0.05	>0.05	<0.05	>0.05	<0.05
Tibialis anterior	<0.05	<0.05	<0.05	>0.05	>0.05
Peroneus longus	<0.05	<0.05	>0.05	<0.05	<0.05
Vastuslateralis	<0.05	>0.05	>0.05	>0.05	<0.05
Vastusmedialis	<0.05	>0.05	<0.05	<0.05	<0.05
Rectus femoris	>0.05	>0.05	<0.05	<0.05	<0.05
Semitendinous/mebranosus	<0.05	<0.05	>0.05	<0.05	>0.05
Biceps femoris	>0.05	<0.05	<0.05	<0.05	<0.05

Table 5-4. Summarized amplitude based P-value comparison between control shoe and minimalist shoe for 3 age group young (Y), middle-aged (M) and older (O).

Muscle		Loading phase	Mid-stance	Terminal stance and pre-swing	Initial swing	Terminal swing
		(0 – 10 %)	(10-30%)	(30 – 60%)	(60 – 73%)	(87 – 100%)
Soleus	Y	*< 0.05	> 0.05	> 0.05	> 0.05	*< 0.05
	M	> 0.05	> 0.05	*< 0.05	*< 0.05	*< 0.05
	O	> 0.05	> 0.05	*< 0.05	*< 0.05	*< 0.05
Gastrocnemius medialis	Y	*< 0.05	*< 0.05	*< 0.05	> 0.05	*< 0.05
	M	> 0.05	> 0.05	> 0.05	> 0.05	*< 0.05
	O	*< 0.05	> 0.05	*< 0.05	*< 0.05	> 0.05
Gastrocnemius	Y	*< 0.05	*< 0.05	> 0.05	> 0.05	*< 0.05

lateralis	M	* < 0.05	> 0.05	> 0.05	* < 0.05	> 0.05
	O	> 0.05	* < 0.05	> 0.05	* < 0.05	* < 0.05
Tibialis anterior	Y	> 0.05	> 0.05	* < 0.05	> 0.05	* < 0.05
	M	> 0.05	* < 0.05	> 0.05	* < 0.05	> 0.05
	O	* < 0.05	> 0.05	* < 0.05	* < 0.05	> 0.05
Peroneus longus	Y	* < 0.05	* < 0.05	> 0.05	> 0.05	* < 0.05
	M	* < 0.05	> 0.05	> 0.05	* < 0.05	> 0.05
	O	* < 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Vastus lateralis	Y	> 0.05	> 0.05	> 0.05	* < 0.05	* < 0.05
	M	> 0.05	* < 0.05	* < 0.05	* < 0.05	> 0.05
	O	* < 0.05	> 0.05	> 0.05	* < 0.05	* < 0.05
Vastus medialis	Y	> 0.05	> 0.05	* < 0.05	> 0.05	* < 0.05
	M	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
	O	* < 0.05	> 0.05	> 0.05	< 0.05	* < 0.05
Rectus femoris	Y	< 0.05	* < 0.05	> 0.05	* < 0.05	* < 0.05
	M	> 0.05	* < 0.05	> 0.05	* < 0.05	> 0.05
	O	* < 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Semitendinosus/ mebranosus	Y	* < 0.05	* < 0.05	* < 0.05	* < 0.05	* < 0.05
	M	> 0.05	* < 0.05	> 0.05	* < 0.05	> 0.05
	O	* < 0.05	> 0.05	* < 0.05	* < 0.05	> 0.05
Biceps femoris	Y	> 0.05	> 0.05	* < 0.05	> 0.05	* < 0.05
	M	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
	O	* < 0.05	* < 0.05	> 0.05	> 0.05	* < 0.05

Table 5-5. IEMG muscle activity for comparison between control shoe and minimalist shoe for group young, middle-aged and. * indicates significant difference in the p-value.

Muscle		Loading phase	Mid-stance	Terminal stance and pre-swing
		(0 – 10 %)	(10-30%)	(30 – 60%)
Soleus	Y	*125.69	*88.79	82.98
	M	*105.89	*108.64	*82.84
	O	101.02	101.39	*90.20
Gastrocnemius medialis	Y	*124.88	*68.58	*126.95
	M	121.04	*104.34	100.07
	O	*135.96	93.85	*79.30
Gastrocnemius lateralis	Y	*112.93	80.34	97.77
	M	*86.67	*102.27	100.58
	O	90.65	*81.98	*108.70
Tibialis anterior	Y	97.28	109.22	*120.62
	M	113.88	*115.28	97.36
	O	*77.98	97.93	*121.15
Peroneus longus	Y	*122.80	80.05	117.90
	M	*77.20	94.79	112.15
	O	*113.43	100.14	90.56
Vastus lateralis	Y	101.44	*105.90	109.92
	M	98.35	*121.48	94.31
	O	*79.42	89.61	103.27
Vastus medialis	Y	100.72	102.75	*107.58
	M	103.58	*102.95	95.82
	O	*84.35	101.30	101.94
Rectus femoris	Y	*131.66	*112.55	*92.22
	M	93.65	*141.03	90.34
	O	*78.97	*119.58	103.18
Semitendinosus/mebranosus	Y	*89.22	*115.54	*107.55
	M	103.57	*117.81	102.59
	O	*70.19	*105.72	*114.60
Biceps femoris	Y	102.66	107.74	*131.55
	M	98.70	102.76	95.99
	O	*117.39	*85.79	99.80

5.3.2 Multiple density sole

Table 5-6 illustrates the P value between the normalized amplitude of lower extremities muscle activity for the Multiple density - FitFlop shoe with respect to the control shoe for the 3 age groups during the 5 phases of the gait cycle. All 5 subjects' values for each age group were averaged out into one before comparing (Inter-subject comparison).

Table 5-7 shows integrated SEMG data with reference to the control shoe. The “*” sign symbolizes statistical differences ($P < 0.05$) for the phase.

Table 5-6. P-value for comparison of normalized amplitude between control shoe and FitFlop shoe for 3 age group young, middle-aged and older.

P- value		Loading phase	Mid-stance	Terminal stance and pre-swing	Initial swing	Terminal swing
		(0 – 10 %)	(10- 30%)	(30 – 60%)	(60 – 73%)	(87 – 100%)
Soleus	Y	> 0.05	*< 0.05	> 0.05	> 0.05	*< 0.05
	M	*<0.05	>0.05	>0.05	>0.05	*< 0.05
	O	> 0.05	> 0.05	> 0.05	*< 0.05	*< 0.05
Gastrocnemius medialis	Y	> 0.05	*< 0.05	> 0.05	> 0.05	*< 0.05
	M	>0.05	>0.05	>0.05	*< 0.05	>0.05
	O	> 0.05	> 0.05	*< 0.05	> 0.05	*< 0.05
Gastrocnemius lateralis	Y	*< 0.05	*< 0.05	> 0.05	*< 0.05	*< 0.05
	M	*< 0.05	>0.05	>0.05	*< 0.05	*< 0.05
	O	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Tibialis anterior	Y	> 0.05	*< 0.05	*< 0.05	*< 0.05	*< 0.05
	M	>0.05	*< 0.05	>0.05	*< 0.05	>0.05
	O	> 0.05	> 0.05	*< 0.05	*< 0.05	> 0.05
Peroneus longus	Y	> 0.05	> 0.05	> 0.05	*< 0.05	*< 0.05
	M	*< 0.05	>0.05	>0.05	*< 0.05	>0.05
	O	*< 0.05	> 0.05	> 0.05	> 0.05	*< 0.05
Vastus lateralis	Y	> 0.05	*< 0.05	> 0.05	> 0.05	*< 0.05
	M	*< 0.05	>0.05	*< 0.05	*< 0.05	*< 0.05
	O	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Vastus medialis	Y	> 0.05	> 0.05	*< 0.05	> 0.05	> 0.05
	M	>0.05	*< 0.05	>0.05	*< 0.05	>0.05
	O	> 0.05	> 0.05	*< 0.05	*< 0.05	> 0.05
Rectus femoris	Y	> 0.05	*< 0.05	*< 0.05	*< 0.05	*< 0.05
	M	>0.05	*< 0.05	*< 0.05	*< 0.05	>0.05
	O	> 0.05	> 0.05	*< 0.05	*< 0.05	> 0.05
Semitendinosus/mebranosus	Y	> 0.05	*< 0.05	> 0.05	*< 0.05	*< 0.05
	M	*< 0.05	>0.05	>0.05	*< 0.05	>0.05
	O	*< 0.05	> 0.05	< 0.05	*< 0.05	> 0.05
Biceps femoris	Y	> 0.05	*< 0.05	*< 0.05	*< 0.05	*< 0.05
	M	>0.05	>0.05	*< 0.05	>0.05	>0.05
	O	> 0.05	*< 0.05	> 0.05	> 0.05	*< 0.05

Table 5-7. IEMG Muscle activity for comparison between control shoe and FitFlop shoe for 3 age group young, middle-aged and older (control shoe =100% of the integrated SEMG area).

Muscle		Loading phase	Mid-stance	Terminal stance and pre-swing
		(0 – 10 %)	(10- 30%)	(30 – 60%)
Soleus	Y	103.37	*77.78	91.08
	M	*105.68	103.65	89.21
	O	*101.33	*105.66	*94.19
Gastrocnemius medialis	Y	95.10	*73.38	108.40
	M	92.02	105.06	88.16
	O	98.36	*115.70	*84.22
Gastrocnemius lateralis	Y	*91.72	*71.50	103.41
	M	*78.94	109.57	83.90
	O	97.00	102.23	104.87
Tibialis anterior	Y	*116.05	*123.76	*118.18
	M	103.87	*108.12	96.19
	O	88.97	95.12	*107.74
Peroneus longus	Y	*109.81	89.69	104.60
	M	*78.26	107.41	99.36
	O	*110.62	102.44	103.19
Vastus lateralis	Y	94.44	*121.97	*110.37
	M	78.26	107.41	*99.36
	O	107.83	92.91	*87.74
Vastus medialis	Y	94.51	*102.47	*104.72
	M	108.22	*93.65	97.28
	O	96.68	95.95	*96.16
Rectus femoris	Y	109.47	*131.47	*109.05
	M	90,81	*142.71	*125.07
	O	*107.15	93.20	*89.16
Semitendinosus/mebranosus	Y	*112.59	*126.52	*104.90
	M	*109.97	95.89	95.05
	O	*58.77	99.25	*130.54
Biceps femoris	Y	98.82	*121.57	*145.90
	M	95.10	93.99	*110.97
	O	95.43	*63.54	102.13

5.3.3 Rocker bottom sole

Table 5-8 illustrates the P value between the normalized amplitude of lower extremities muscle activity for the MBT shoe with respect to the control shoe for the 3 age group during the 5 phases of the gait cycle. All 5 subjects' values for each age group were averaged out into one before comparing.

Table 5-9 shows the percentage of integrated SEMG of MBT shoe with reference to the control shoe. The * sign symbolizes statistical differences ($p < 0.05$) for the phase.

Table 5-8. P-value for comparison of normalized amplitude between control shoe and MBT shoe for 3 age group young, middle-aged and older.

Muscle		Loading phase	Mid-stance	Terminal stance and pre-swing	Initial swing	Terminal swing
		(0 – 10 %)	(10-30%)	(30 – 60%)	(60 – 73%)	(87 – 100%)
Soleus	Y	> 0.05	*< 0.05	> 0.05	*< 0.05	*< 0.05
	M	*< 0.05	> 0.05	*< 0.05	*< 0.05	*< 0.05
	O	*< 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Gastrocnemius medialis	Y	> 0.05	*< 0.05	> 0.05	> 0.05	*< 0.05
	M	> 0.05	*< 0.05	> 0.05	> 0.05	*< 0.05
	O	*< 0.05	> 0.05	> 0.05	> 0.05	*< 0.05
Gastrocnemius lateralis	Y	*< 0.05	*< 0.05	> 0.05	*< 0.05	*< 0.05
	M	> 0.05	*< 0.05	> 0.05	> 0.05	*< 0.05
	O	> 0.05	> 0.05	> 0.05	*< 0.05	*< 0.05
Tibialis anterior	Y	> 0.05	*< 0.05	*< 0.05	> 0.05	*< 0.05
	M	> 0.05	> 0.05	*< 0.05	> 0.05	*< 0.05
	O	*< 0.05	*< 0.05	*< 0.05	*< 0.05	*< 0.05
Peroneus longus	Y	> 0.05	*< 0.05	*< 0.05	*< 0.05	*< 0.05
	M	*< 0.05	> 0.05	> 0.05	> 0.05	> 0.05
	O	*< 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Vastus lateralis	Y	*< 0.05	*< 0.05	> 0.05	*< 0.05	*< 0.05
	M	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
	O	*< 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Vastus medialis	Y	> 0.05	> 0.05	> 0.05	*< 0.05	> 0.05
	M	> 0.05	*< 0.05	> 0.05	*< 0.05	> 0.05
	O	*< 0.05	> 0.05	> 0.05	*< 0.05	*< 0.05
Rectus femoris	Y	*< 0.05	*< 0.05	> 0.05	*< 0.05	*< 0.05
	M	> 0.05	*< 0.05	> 0.05	> 0.05	> 0.05
	O	> 0.05	> 0.05	> 0.05	> 0.05	> 0.05
Semitendinosus/mebranosus	Y	> 0.05	*< 0.05	*< 0.05	< 0.05	*< 0.05
	M	> 0.05	*< 0.05	*< 0.05	> 0.05	> 0.05
	O	*< 0.05	> 0.05	> 0.05	> 0.05	*< 0.05
Biceps femoris	Y	*< 0.05	*< 0.05	> 0.05	< 0.05	*< 0.05
	M	> 0.05	> 0.05	> 0.05	> 0.05	*< 0.05
	O	> 0.05	*< 0.05	> 0.05	> 0.05	> 0.05

Table 5-9. IEMG Muscle activity for comparison between control shoe and MBT shoe for 3 age group young, middle-aged and older (control shoe=100% of the Integrated SEMG curve area)

Muscle		Loading phase	Mid-stance	Terminal stance and pre-swing
		(0 – 10 %)	(10-30%)	(30 – 60%)
Soleus	Y	103.64	*69.14	97.08
	M	*110.27	95.13	*87.43
	O	*118.63	106.23	92.02
Gastrocnemius medialis	Y	107.79	*59.06	*114.58
	M	107.17	*94.88	91.19
	O	*134.59	101.36	86.13
Gastrocnemius lateralis	Y	*88.54	*52.73	116.99
	M	*111.79	*83.41	103.26
	O	105.14	98.88	92.51
Tibialis anterior	Y	105.77	*118.28	*108.97
	M	86.05	*107.40	*112.34
	O	*61.00	*88.92	*130.45
Peroneus longus	Y	98.37	*82.85	*124.58
	M	*88.26	90.99	114.17
	O	*123.84	95,60	92.82
Vastus lateralis	Y	*83.14	*126.99	106.86
	M	96.59	*121.19	*111.79
	O	*86.41	106.95	91.93
Vastus medialis	Y	95.89	103.52	*95.57
	M	*112.45	*103.07	97.23
	O	*83.41	97.85	99.87
Rectus femoris	Y	88.13	*127.61	*105.71
	M	90.33	*151.94	103.16
	O	92.89	108.49	97.44
Semitendinosus/mebranosus	Y	104.13	*132.52	*111.69
	M	94.65	*90.78	*95.56
	O	*74.27	102.19	*102.96
Biceps femoris	Y	94.12	*125.30	*149.98
	M	*107.08	*105.03	*101.59
	O	103.55	*72.38	100.47

5.4 Age-related difference based on normalized mean amplitude peak-aligned SEMG muscle activity

In tables 5-10 to 5-12, age-related differences were compared in a minimalist shoe type.

5.4.1 Minimalist shoe: Young Vs Middle-aged

Table 5-10. Comparison of Mean normalized Amplitude between Young and Middle-aged in minimalist shoes, higher muscle activity is indicated by alphabets M – Middle-aged and Y - Young (highlighted area indicates significantly different phase)

Comparison of Mean normalized amplitude					
Muscle	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	M	Y	Y	M	M
Gastrocnemius medial	Y	Y	Y	Y	M
Gastrocnemius lateralis	Y	Y	Y	Y	M
Tibialis anterior	M	M	M	Y	Y
Peroneus longus	Y	Y	Y	M	Y
Vastus lateralis	Y	M	M	M	M
Vastus medialis	Y	M	Y	Y	M
Rectus femoris	Y	Y	M	M	M
Semitendinosus	Y	M	M	Y	M
Biceps femoris	Y	M	M	M	Y

*Y indicates Young has higher mean normalized amplitude; M indicates Middle-aged has higher mean normalized amplitude

Legend	
	p<0.05
	p>0.05

5.4.2 Minimalist shoe: Middle-aged Vs Older

Table 5-11. Comparison of Mean Normalized Amplitude between Middle-aged and Older in Barefoot Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	M	M	O	O	M
Gastrocnemius medial	M	O	O	M	M
Gastrocnemius lateralis	M	O	M	O	M
Tibialis anterior	O	O	M	O	O
Peroneus longus	O	O	M	M	M
Vastus lateralis	O	M	M	O	O
Vastus medialis	O	M	M	O	M
Rectus femoris	O	M	M	O	O
Semitendinosus	O	M	M	O	O
Biceps femoris	O	M	M	M	O

*M indicates Middle-aged has higher mean normalized amplitude; O indicates Old has higher mean normalized amplitude

Legend	
	p<0.05
	p>0.05

5.4.3 Minimalist shoe: Young Vs Older

Table 5-12. Comparison of Mean Normalized Amplitude between Young and Older in minimalist shoes

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	Y	Y	Y	O	O
Gastrocnemius medial	Y	Y	O	Y	O
Gastrocnemius lateralis	Y	O	Y	O	O
Tibialis anterior	O	O	O	Y	Y
Peroneus longus	Y	O	Y	Y	Y
Vastus lateralis	Y	Y	Y	O	O
Vastus medialis	O	Y	Y	Y	O
Rectus femoris	O	Y	Y	O	O
Semitendinosus	Y	Y	O	O	O
Biceps femoris	O	Y	Y	Y	O

*Y indicates Young has higher mean normalized amplitude; O indicates Old has higher mean normalized amplitude.

Legend	
	p<0.05
	p>0.05

5.4.4 Control footwear: Young Vs Middle-aged

In tables 5-13 to 5-15, age-related differences were compared in control footwear.

Young vs Middle-aged

Younger age-group exhibited higher activity in 9 out of 10 lower extremity

muscles studies, muscles with statistical insignificance were Soleus, VM, BF and semitendinosus. As younger adults tend to have higher muscle activity at the start of the gait cycle. In the swing phase, young also exhibited higher muscle activity noticeably in GL, TA, PL, BF and semitendinosus. Suggesting that younger adults activate muscles connected with ankle movement greater extent than compared middle-aged. Hip and knee activated more to decelerate leg kinematics.

Middle-aged Vs Older

Almost all muscles have recorded 3 or more significantly different (p -value <0.05) phases Soleus, GL, TA, PL, VL and VM in older adults had higher muscle activity during the start of the stance phase, in end stance phase, 9 out of 10 muscles (except BF) have higher activity in middle-aged adults; significantly higher ones (p -value <0.05) were GM, GL, VL, VM and RF. The results are consistent for GM and GL because older adults have lower plantarflexor power during push-off due to weaker ankle [150]. As such lower muscle activity in older adults in muscles responsible for ankle plantarflexion.

Young Vs Older

Significant differences were noted (p -value <0.050) in the quadriceps muscles F. Young adults showed higher muscle activity in the quadriceps muscles during the intermediate and end stance phase. This was correlated and found consistent with existing knowledge [151].

Table 5-13. Comparison of Mean Normalized Amplitude between Young and Middle-aged in Control Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	Y	Y	M	M	M
Gastrocnemius medial	Y	Y	M	Y	M
Gastrocnemius Lateralis	Y	M	Y	Y	Y
Tibialis anterior	Y	Y	Y	Y	Y
Peroneus longus	Y	M	Y	Y	Y
Vastus lateralis	Y	M	M	Y	M
Vastus medialis	Y	Y	M	Y	Y
Rectus femoris	M	Y	M	Y	Y
Semitendinosus	Y	M	M	Y	Y
Biceps femoris	Y	M	Y	Y	Y

*Y indicates Young has higher mean normalized amplitude; M indicates Middle-aged has higher mean normalized amplitude

Legend	
	p<0.05
	p>0.05

5.4.5 Control footwear: Middle-aged Vs Older

Table 5-14. Comparison of Mean Normalized Amplitude between Middle-aged and Older in Control Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	O	O	M	M	M
Gastrocnemius medial	O	O	M	M	M
Gastrocnemius lateralis	O	O	M	O	O
Tibialis anterior	O	M	M	M	O
Peroneus longus	O	O	M	M	O
Vastus lateralis	O	M	M	O	M
Vastus medialis	O	M	M	M	O
Rectus femoris	O	O	M	O	O
Semitendinosus	M	M	M	O	O
Biceps femoris	O	M	O	O	M

*M indicates Middle-aged has higher mean normalized amplitude; O indicates Old has higher mean normalized amplitude

Legend	
	p<0.05
	p>0.05

5.4.6 Control footwear: Young Vs Older

Table 5-15. Comparison of Mean Normalized Amplitude between Young and Older in Control Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	O	Y	Y	O	Y
Gastrocnemius medial	Y	O	Y	Y	Y
Gastrocnemius lateralis	O	O	Y	O	Y
Tibialis anterior	O	Y	Y	Y	O
Peroneus longus	Y	O	Y	Y	O
Vastus lateralis	O	Y	Y	O	O
Vastus medialis	O	Y	Y	Y	O
Rectus femoris	O	Y	Y	O	O
Semitendinosus	Y	O	Y	O	O
Biceps femoris	Y	O	O	Y	Y

*Y indicates Young has higher mean normalized amplitude; O indicates Old has higher mean normalized amplitude

Legend	
	p<0.05
	p>0.05

5.4.7 Multiple-density sole

In tables 5-16 to 5-18, age-related differences were compared in a multiple density fitflop footwear.

Young Vs Middle-aged

At the start of gait, young adults showed a significantly higher muscle activity in GM, GL and PL. Young adults showed higher muscle activity in the soleus muscle. It can be observed that the young adults use more of the muscles responsible for ankle movement in the start phase. In the first half of the swing phase, five muscles have had significant difference (p-value <0.05) with young adults exhibiting the higher activity overall, in the Second half of the swing phase, middle-aged activated GM, VL, VM and RF to a significantly greater extent (p-value<0.05) than younger adults.

Middle-aged Vs Older

Older adults showed higher muscle activity in the stance phase. Differences between middle-aged and older adults are significant ($p\text{-value} < 0.05$) in GM, GL, TA, VL, VM and RF. In the swing phase middle-aged adults showed significantly higher activity in GM, VM, RF and semitendinosus muscles.

Young Vs Older

In the comparison between young and older adults a major observation was that for all 10 muscles during start stance phase, young adults had higher normalized amplitude than older adults. The difference is significantly higher in the ankle movement muscle group such as GM, GL, TA and PL. In the quadriceps group, muscle activity is higher for young adults. This is possibly due to the muscle weakness of older adults in performing hip extension during this phase [151].

5.4.8 Young Vs Middle-aged

Table 5-16. Comparison of Mean Normalized Amplitude between Young and Middle-aged in Fitflop Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	Y	Y	Y	M	M
Gastrocnemius medial	Y	Y	M	Y	M
Gastrocnemius lateralis	Y	Y	M	Y	M
Tibialis anterior	M	Y	M	Y	Y
Peroneus longus	Y	Y	M	M	Y
Vastus lateralis	Y	Y	M	M	M
Vastus medialis	M	M	Y	Y	M
Rectus femoris	M	Y	M	Y	M
Semitendinosus	M	M	Y	Y	Y
Biceps femoris	M	M	M	Y	M

*Y indicates Young has higher mean normalized amplitude; M indicates Middle-aged has higher mean normalized amplitude

Legend	
	p<0.05
	p>0.05

5.4.9 Middle-aged Vs Older

Table 5-17. Comparison of Mean Normalized Amplitude between Middle-aged and Older in Fitflop Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	O	M	O	O	M
Gastrocnemius medial	O	O	M	M	M
Gastrocnemius lateralis	M	O	M	O	O
Tibialis anterior	M	O	M	M	M
Peroneus longus	O	O	O	O	M
Vastus lateralis	O	O	M	M	M
Vastus medialis	M	O	M	M	M
Rectus femoris	M	O	M	O	M
Semitendinosus	M	O	O	O	M
Biceps femoris	M	O	O	M	O

*M indicates Middle-aged has higher mean normalized amplitude; O indicates Older has higher mean normalized amplitude

Legend	
	p<0.05
	p>0.05

5.4.10 Young Vs Older

Table 5-18. Comparison of Mean Normalized Amplitude between Young and Older Adults in Fitflop Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	Y	Y	O	O	O
Gastrocnemius medial	Y	O	Y	Y	O
Gastrocnemius lateralis	Y	Y	O	Y	O
Tibialis anterior	Y	O	Y	Y	Y
Peroneus longus	Y	Y	O	O	Y
Vastus lateralis	Y	O	Y	O	O
Vastus medialis	Y	O	Y	Y	O
Rectus femoris	Y	O	Y	O	O
Semitendinosus	Y	O	O	Y	Y
Biceps femoris	Y	O	O	Y	O

*Y indicates Young has higher mean normalized amplitude; O indicates Older has higher mean normalized amplitude

Legend	
	p<0.05
	p>0.05

5.4.11 Rocker Bottom sole (MBT)

In tables 5-19 to 5-22, age-related differences were compared in rocker bottom footwear.

Young Vs Middle-aged

Soleus and GM showed similar muscle activity pattern, with young adults exhibiting higher muscle activity in stance to intermediate phase while middle-aged adults exerting more during the end stance and swing phase. Middle-aged adults also exhibited higher activity in VL, VM, RG, BF and semitendinosus in the stance phase (p-value<0.05).

Middle-aged Vs Older

Soleus, GM, GL, TA and PL. MBT footwear had significant effect when compared with middle-aged and older adults. For GM, there is significant difference in muscle activity ($p\text{-value} < 0.05$) in the whole gait cycle; older adults exhibited higher during the stance phase but lower during swing phase. During the intermediate stance phase, older adults had a predominantly higher muscle activity than middle-aged. The higher activity of soleus and TA in older adults is consistent with other studies, which suggest a greater activation of TA and soleus.

Young Vs Older

Eight out of ten muscles have at least 3 or more phases that have significant difference ($p\text{-value} < 0.05$). This shows that MBT shoes have affected the gait muscle activity of young and older adults to a large extent. Studies have shown that transform flat hard artificial surfaces into uneven surfaces, enabling muscles to be more active [152]. In the stance phase, older adults have significantly higher activity in TA, PL, VL, RF, BF and semitendinosus. This could have been attributed to the heavy weight of MBT (compared to other shoes), which causes older adults to exert more muscle activity during the phase. PL activity may be higher to transfer the additional weight of the MBT and TA is used to stabilize the ankle.

Young Vs Middle-aged

Table 5-19. Comparison of Mean Normalized Amplitude between Young and Middle-aged in MBT Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	Y	Y	M	M	M
Gastrocnemius medial	Y	Y	M	M	M
Gastrocnemius lateralis	Y	Y	M	Y	M
Tibialis anterior	M	M	Y	Y	Y
Peroneus longus	Y	Y	M	M	Y
Vastus lateralis	Y	M	M	Y	M
Vastus medialis	M	M	Y	Y	M
Rectus femoris	Y	M	M	Y	Y
Semitendinosus	Y	M	Y	M	Y
Biceps femoris	Y	M	Y	Y	Y

*Y indicates Young has higher mean normalized amplitude; M indicates Middle-aged has higher mean normalized amplitude

Legend	
	$p < 0.05$
	$p > 0.05$

5.4.12 Middle-aged Vs Older

Table 5-20. Comparison of Mean Normalized Amplitude between Middle-aged and Older Adults in MBT Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	O	O	M	O	M
Gastrocnemius medial	O	O	O	M	M
Gastrocnemius lateralis	M	O	M	O	M
Tibialis anterior	M	O	M	O	O
Peroneus longus	O	O	M	M	M
Vastus lateralis	M	O	M	O	M
Vastus medialis	M	O	M	O	M
Rectus femoris	O	O	M	M	O
Semitendinosus	O	O	M	M	O
Biceps femoris	O	M	O	O	M

*M indicates Middle-aged has higher mean normalized amplitude; O indicates Older has higher mean normalized amplitude.

Legend	
	p<0.05
	p>0.05

5.4.13 Young Vs Older

Table 5-21. Comparison of Mean Normalized Amplitude between Young and Older Adults in MBT Footwear

Comparison of Mean normalized amplitude					
	(0 – 20 %)	(20- 40%)	(40 – 60%)	(60 – 80%)	(80 – 100%)
Soleus	Y	Y	O	O	Y
Gastrocnemius medial	Y	Y	O	O	O
Gastrocnemius lateralis	Y	O	Y	O	O
Tibialis anterior	O	O	Y	Y	Y
Peroneus longus	Y	O	Y	Y	Y
Vastus lateralis	Y	O	O	Y	Y
Vastus medialis	O	O	Y	Y	O
Rectus femoris	O	O	Y	Y	Y
Semitendinosus	Y	O	Y	Y	Y
Biceps femoris	Y	O	O	Y	Y

*Y indicates Young has higher mean normalized amplitude

*O indicates Old has higher mean normalized amplitude

Legend	
	p<0.05
	p>0.05

5.5 Integrated SEMG method

Integrated EMG (iEMG) is defined as the area under the stance-phase (0-60%) curve of the rectified EMG signal, that is, the mathematical integral of the absolute value of the raw EMG signal. The values are tabulated in table 5-22 to 5-24.

Table 5-22. Area under EMG curve for Young Adults in Control Footwear

Control, young			
	(0 – 20 %)	(20- 40%)	(40 – 60%)
Soleus	14.24	30.85	24.09
Gastrocnemius medial	13.36	31.36	20.99
Gastrocnemius lateralis	19.75	16.68	42.50
Tibialis anterior	23.50	11.91	17.51
Peroneus longus	19.20	19.61	29.72
Vastus lateralis	34.36	17.55	12.69
Vastus medialis	20.73	19.79	19.34
Rectus femoris	22.33	17.96	19.27
Semitendinosus	26.61	14.33	16.37
Biceps femoris	24.56	13.90	12.83

Table 5-23. Area under EMG curve for Middle-aged Adults in Control Footwear

Control, middle-aged			
	(0 – 20 %)	(20- 40%)	(40 – 60%)
Soleus	14.40	16.35	32.02
Gastrocnemius medial	11.44	21.45	29.90
Gastrocnemius lateral	14.66	35.51	30.06
Tibialis anterior	14.97	18.31	18.23
Peroneus longus	12.32	27.00	24.17
Vastus lateralis	17.71	20.75	15.79
Vastus medialis	18.21	19.05	23.62
Rectus femoris	32.56	11.12	24.01
Semitendinosus	22.97	17.83	16.69
Biceps femoris	23.47	19.38	12.76

Table 5-24. Area under EMG curve for Older Adults in Control Footwear

Control, older			
	(0 – 20 %)	(20- 40%)	(40 – 60%)
Soleus	16.55	24.40	24.85
Gastrocnemius medial	14.24	38.07	17.35
Gastrocnemius	22.41	33.94	16.02
lateralis			
Tibialis anterior	26.74	11.78	17.25
Peroneus longus	18.03	29.97	21.78
Vastus lateralis	37.99	11.98	7.49
Vastus medialis	27.02	17.47	17.32
Rectus femoris	36.18	12.71	11.61
Semitendinosus	21.99	14.30	17.29
Biceps femoris	23.14	13.83	19.96

Based on the testing protocol, the experiments were carried out on different age groups of subjects. The results of the experiment were tabulated in this section. In order to validate the significant differences of the shoes types with respect to the control shoes, T-test is used to do the comparison. A P-value of 0.05 is chosen as the threshold for the statistical significance differences. For ($P < 0.05$), it verifies that there is a significant difference in the control shoe and the footwear tested.

5.6 Young Adults

Table 5-24 illustrates the P value of the minimalist shoe, FitFlop and MBT with respect to the control shoe for the young adults during the 5 phases of the gait cycle. In the T-test conducted, a P value of 0.05 is set to verify the statistical differences ($P < 0.05$) between the control shoe and the different footwear.

In Table 5-25 and 5-26, it shows the IEMG values of all the shoes with respect to the control shoes.

Table 5-25. P-value for the comparison for the young adults (MS: Minimalist shoe, FF:FitFlop)

Muscle		0-20%	20-40%	40-60%
Soleus	MS	<0.05	<0.05	<0.05
	FF	<0.05	<0.05	<0.05
	MBT	>0.05	>0.05	>0.05
Gastrocnemius medial	MS	>0.05	>0.05	>0.05
	FF	<0.05	>0.05	>0.05
	MBT	>0.05	<0.05	>0.05
Tibialis	MS	>0.05	<0.05	>0.05
	FF	>0.05	<0.05	>0.05
	MBT	>0.05	>0.05	>0.05
vastus medialis	MS	>0.05	>0.05	<0.05
	FF	>0.05	>0.05	<0.05
	MBT	<0.05	<0.05	>0.05
Semitendinosus	MS	<0.05	<0.05	<0.05
	FF	>0.05	>0.05	>0.05
	MBT	>0.05	>0.05	>0.05
Gastrocnemius lateralis	MS	>0.05	>0.05	>0.05
	FF	<0.05	>0.05	>0.05
	MBT	>0.05	>0.05	>0.05
Peroneus longus	MS	>0.05	>0.05	>0.05
	FF	<0.05	<0.05	<0.05
	MBT	>0.05	>0.05	>0.05

vastus lateralis	MS	>0.05	<0.05	<0.05
	FF	<0.05	<0.05	<0.05
	MBT	>0.05	>0.05	<0.05
Biceps femoris	MS	<0.05	>0.05	<0.05
	FF	<0.05	>0.05	<0.05
	MBT	<0.05	>0.05	<0.05
rectus femoris	MS	>0.05	<0.05	<0.05
	FF	<0.05	>0.05	<0.05
	MBT	>0.05	>0.05	>0.05

Table 5-26. IEMG values for comparion of young adults (MS: Minimalist shoe, FF:FitFlop)

Muscle		0-20%	20-40%	40-60%
Soleus	MS	270.17	326.20	750.88
	FF	283.87	363.115	746.78
	MBT	317.26	419.79	951.52
	Control	299.81	396.59	745.01
Gastrocnemius medial	MS	152.46	270.08	531.85
	FF	132.97	354.16	386.43
	MBT	165.95	298.01	508.51
	Control	128.50	220.13	324.10
Tibialis	MS	485.78	195.84	286.98
	FF	442.08	222.35	356.40
	MBT	468.51	180.27	451.46
	Control	452.62	180.50	342.62
vastus medialis	MS	476.32	306.43	151.70
	FF	350.22	266.71	349.59
	MBT	822.74	300.97	393.67
	Control	317.57	312.49	473.09
Semitendinosus	MS	285.73	266.60	109.07
	FF	257.25	145.32	153.89
	MBT	290.60	225.78	145.70
	Control	346.73	324.60	121.54
Gastrocnemius lateralis	MS	115.60	128.39	435.21
	FF	113.94	158.38	416.68
	MBT	132.36	179.53	626.26

	Control	128.52	136.22	445.07
Peroneus longus	MS	200.89	193.46	804.39
	FF	204.64	288.21	794.26
	MBT	239.09	303.89	999.42
	Control	304.94	212.55	713.18
vastus lateralis	MS	314.67	126.07	31.02
	FF	264.12	112.90	46.66
	MBT	271.07	199.41	54.27
	Control	268.37	113.84	27.77
Biceps femoris	MS	195.10	77.20	68.65
	FF	251.27	46.04	116.98
	MBT	336.30	61.38	99.00
	Control	352.87	62.62	95.15
Rectus femoris	MS	303.26	217.53	511.77
	FF	217.56	117.66	154.75
	MBT	219.66	172.07	415.67
	Control	282.88	227.92	819.19

5.7 Middle Aged Adults

Table 5-27 illustrates the P value of the minimalist shoe, FitFlop and MBT with respect to the control shoe for the middle aged adults during the 5 phases of the gait cycle. In the T-test conducted, a P value of 0.05 is set to verify the statistical differences ($P < 0.05$) between the control shoe and the different footwear.

In Table 5-28 it shows the IEMG values of all the shoes with respect to the control shoes.

Table 5-27 .P-value for the comparison for the Middle aged adults (MS: Minimalist shoe, FF:FitFlop)

Muscle		0-20%	20-40%	40-60%
Soleus	MS	<0.05	>0.05	<0.05
	FF	>0.05	<0.05	<0.05
	MBT	<0.05	<0.05	<0.05
Gastrocnemius medial	MS	<0.05	<0.05	<0.05
	FF	>0.05	<0.05	<0.05
	MBT	>0.05	>0.05	<0.05
Tibialis	MS	<0.05	<0.05	<0.05
	FF	<0.05	<0.05	>0.05
	MBT	<0.05	>0.05	>0.05
vastus medialis	MS	>0.05	>0.05	>0.05
	FF	<0.05	>0.05	>0.05
	MBT	>0.05	>0.05	>0.05
Semitendinosus	MS	<0.05	<0.05	>0.05
	FF	<0.05	>0.05	<0.05
	MBT	>0.05	>0.05	>0.05
Gastrocnemius lateralis	MS	>0.05	<0.05	<0.05
	FF	>0.05	<0.05	<0.05
	MBT	>0.05	<0.05	<0.05

Peroneus longus	MS	<0.05	<0.05	>0.05
	FF	<0.05	<0.05	<0.05
	MBT	<0.05	<0.05	>0.05
vastus lateralis	MS	<0.05	<0.05	<0.05
	FF	>0.05	<0.05	<0.05
	MBT	<0.05	>0.05	<0.05
Biceps femoris	MS	<0.05	<0.05	<0.05
	FF	>0.05	>0.05	<0.05
	MBT	<0.05	<0.05	<0.05
rectus femoris	MS	>0.05	<0.05	>0.05
	FF	>0.05	>0.05	>0.05
	MBT	>0.05	>0.05	>0.05

Table 5-28. IEMG values for comparison of middle aged adults (MS: Minimalist shoe, FF:FitFlop)

Muscle		0-20%	20-40%	40-60%
Soleus	MS	312.51	309.83	291.17
	FF	316.22	264.27	285.68
	MBT	322.84	245.85	280.35
	Control	280.53	331.24	314.10
Gastrocnemius medial	MS	165.12	183.73	191.4
	FF	166.03	183.73	223.41
	MBT	212.453	179.51	145.78
	Control	188.85	247.76	636.78

Tibialis	MS	266.12	355.81	430.92
	FF	421.33	370.09	615.09
	MBT	1264.92	679.72	1016.90
	Control	193.02	253.88	345.76
vastus medialis	MS	367.92	647.30	379.34
	FF	398.02	297.98	343.83
	MBT	482.90	370.82	351.82
	Control	398.415	390.98	386.48
Semitendinosus	MS	571.23	944.80	744.64
	FF	420.69	419.84	765.68
	MBT	489.33	394.63	481.95
	Control	843.23	537.46	647.95
Gastrocnemius lateralis	MS	117.78	155.26	72.72
	FF	160.40	123.25	133.10
	MBT	151.41	118.35	88.11
	Control	136.48	444.35	398.87
Peroneus longus	MS	180.90	117.41	120.81
	FF	143.54	158.37	572.67
	MBT	143.66	116.23	236.09
	Control	429.32	621.55	151.34
vastus lateralis	MS	64.95	180.57	208.86
	FF	92.03	60.67	129.44
	MBT	61.16	60.47	307.37
	Control	116.65	47.46	60.03
Biceps femoris	MS	365.40	1157.25	821.77

	FF	274.55	196.83	416.61 5.8
	MBT	387.33	1085.30	833.35
	Control	346.07	347.65	274.92
rectus femoris	MS	120.67	136.30	113.40
	FF	206.27	66.16	230.59
	MBT	176.96	123.52	200.89
	Control	215.35	70.56	191.53

Older Adults

The P value of the minimalist shoe, FitFlop and MBT with respect to the control shoe for the older adults during the 5 phases of the gait cycle. In the T-test conducted, a P value of 0.05 is set to verify the statistical differences ($P < 0.05$) between the control shoe and the different footwear.

In Table 5-29, it shows the IEMG values of all the shoes with respect to the control shoes.

Table 5-29. P-value for the comparison for the older adults (MS: Minimalist shoe, FF:FitFlop)

Muscle		0-20%	20-40%	40-60%
Soleus	MS	>0.05	>0.05	>0.05
	FF	<0.05	<0.05	<0.05
	MBT	>0.05	<0.05	<0.05
Gastrocnemius medial	MS	<0.05	>0.05	<0.05
	FF	<0.05	>0.05	<0.05
	MBT	<0.05	<0.05	<0.05

Tibialis	MS	>0.05	<0.05	<0.05
	FF	<0.05	<0.05	<0.05
	MBT	<0.05	<0.05	<0.05
vastus medialis	MS	>0.05	>0.05	<0.05
	FF	<0.05	<0.05	<0.05
	MBT	<0.05	<0.05	<0.05
Semitendinosus	MS	<0.05	<0.05	<0.05
	FF	>0.05	<0.05	<0.05
	MBT	>0.05	>0.05	>0.05
Gastrocnemius lateralis	MS	>0.05	<0.05	<0.05
	FF	<0.05	<0.05	<0.05
	MBT	<0.05	>0.05	<0.05
Peroneus longus	MS	>0.05	>0.05	>0.05
	FF	<0.05	<0.05	<0.05
	MBT	<0.05	<0.05	>0.05
vastus lateralis	MS	>0.05	<0.05	>0.05
	FF	<0.05	<0.05	<0.05
	MBT	<0.05	<0.05	<0.05
Biceps femoris	MS	>0.05	<0.05	>0.05
	FF	<0.05	<0.05	>0.05
	MBT	<0.05	<0.05	>0.05
rectus femoris	MS	<0.05	>0.05	>0.05
	FF	>0.05	<0.05	>0.05
	MBT	>0.05	<0.05	<0.05

Table 5-30. IEMG values for comparison of older adults (MS: Minimalist shoe, FF:FitFlop)

Muscle		0-20%	20-40%	40-60%
Soleus	MS	243.078	485.926	294.724
	FF	338.13	355.00	562.64
	MBT	385.29	380.84	619.69
	Control	277.56	476.54	366.20
Gastrocnemius medial	MS	192.75	242.637	117.617
	FF	183.828	262.78	239.40
	MBT	230.69	193.94	284.91
	Control	128.50	220.13	324.10
Tibialis	MS	232.70	155.27	134.56
	FF	307.26	410.25	229.90
	MBT	341.07	388.65	246.18
	Control	425.69	161.72	134.34
vastus medialis	MS	385.88	256.90	229.84
	FF	352.98	566.53	415.289
	MBT	426.58	576.36	386.24
	Control	512.59	276.50	219.25
Semitendinosus	MS	137.14	122.39	114.48
	FF	165.84	163.85	264.21
	MBT	649.36	488.38	421.28
	Control	492.61	254.06	242.86
Gastrocnemius lateralis	MS	191.35	148.18	153.82
	FF	122.54	145.78	317.71
	MBT	126.99	245.30	308.03
	Control	140.06	234.66	87.53
Peroneus longus	MS	204.12	640.59	419.58
	FF	166.96	127.37	614.04
	MBT	157.54	241.17	688.61
	Control	156.91	472.57	407.05
vastus lateralis	MS	608.99	153.26	92.42
	FF	749.92	798.20	351.59
	MBT	307.75	1191.22	764.05
	Control	899.82	354.75	84.80
Biceps femoris	MS	76.81	84.26	90.64
	FF	331.77	179.65	122.45
	MBT	298.87	140.56	125.25
	Control	91.86	79.01	81.44
rectus femoris	MS	115.07	65.66	105.74
	FF	367.56	316.38	129.49
	MBT	469.05	383.77	124.14
	Control	272.69	59.21	77.26

5.9 Hypothesis 4: Summary Amplitude analysis versus Integrated EMG analysis, Intra-subject versus Inter-subject differences.

Based on results obtained from section 5.2 to 5.8, it can be inferred that basic inference differences can be observed in the results obtained between normalized amplitude and integrated EMG methods.

It can be concluded that based on intra-subject iEMG comparison that, popular midsole and outsole footwear features have a localized effect only on major calf and shin muscles, but not on other key lower-extremity gait muscles. The study also points out the effect of comparison methodology based on contrasting results between intra-and inter-subject comparison.

In intra-subject iEMG comparison against a normal control footwear, 80% of the subjects exhibited significantly higher ($p < 0.05$) muscle activity in MBT™ shoe on the calf muscles (SOL, GM and GL) and shin muscles (PL and TA). FitFlop™ showed significant differences ($p < 0.05$) in less than 50% of the subjects across the calf muscle group as well. Whereas, Adidas Adipure Trainer™ exhibited a significant difference ($p < 0.05$) in calf muscles of more than 80% of the subjects. All other muscles and muscle groups exhibited difference in less than 50% subjects in all the footwear condition compared.

In comparison and significant contrast, with the inter-subject findings from a previously published study by the same authors, calf muscles differences were not significantly observable in the inter-subject findings, whereas all other muscles

including biceps femoris, tibialis anterior, peroneus longus, etc. did show a significant difference ($p < 0.05$) [153].

5.10 Discussion

Based on results obtained in sections 5.1 to 5.9, Majority of the previous studies on dominance have noted that there were no differences between leg muscle activity pattern during normal gait [58, 154-156]. Hypothesis 1 testing results on presence of an overall high muscle activity in dominant leg seems to contradict some existing literature [58, 154-156]. However, it was noted that some studies have also previously reported that lower limb muscles are not used equally in gait [157-159]. This difference may be attributed to the presence of cerebral hemispheric dominance [160, 161].

Soleus, gastrocnemius medialis, gastrocnemius lateralis, tibialis anterior, peroneus longus, vastus lateralis, vastus medialis, rectus femoris, semitendinosus/membranosus and biceps femoris (a sample gastrocnemius muscle SEMG profile comparison is illustrated in figure 5-2). showed significant difference between the barefoot and shoed conditions, thus adding strength to the project's hypothesis about footwear feature influencing muscle activity.

Comparing minimalist shoe versus control shoe condition normalised amplitude values across the gait cycle phases, it was found that soleus, gastrocnemius medialis, gastrocnemius lateralis and vastus lateralis significantly ($P < 0.05$) differed across same phases in all the age groups. For tibialis anterior, vastus medialis and bicep femoris, the number of phase differences ($P < 0.05$) increased with age. Peroneus longus, rectus femoris, semitendinosus exhibited lesser

number of phase differences ($P < 0.05$) as the age increased.

For multiple density versus control shoe condition, the normalised amplitude of soleus muscle exhibited significant phase difference across two phases for all age groups. For the other muscles number of phases with significant differences decreased with age. Multiple density footwear was noted only to affect 20% to 30% of the gait cycle differences for the middle-aged and older adults, with the exception of semitendinosus.

For rocker bottom versus control shoe condition soleus, gastrocnemius lateralis, peroneus longus, vastus lateralis, rectus femoris, semitendinosus and bicep femoris showed a decrease in the number phase differences with age. In older adults, the number of phases with significant differences ranged from for 0 to 2 and 3 to 4 in young subjects. In gastrocnemius medialis and vastus medialis the average number of phase differences remained at 3 across all age groups. Phase differences for the tibialis anterior increased with age. The MBT showed relatively fewer differences in phases for the middle-aged and older adults compared to young age-group.

5.10.1 Minimalist shoe

From section 5.3, based on two t-tests were done to compare statistical ($P < 0.05$) differences of the different shoes but not all the muscles exhibited the same

pattern for 3 different age groups. The effects of the minimalist shoe was not significant throughout the different age groups.

The two t-tests did not yield the exact same results as they are comparing with different aspects (Normalized amplitude and IEMG). The first comparison done was on the normalized amplitude of the gait cycle the second was made by comparing IEMG or integrated EMG of the gait cycle. Measurement of the area under the SEMG curve gives a good indication to the total muscular effort during the gait cycle. Even amplitude and IEMG method did not have the same results, both t-tests show similar pattern in the number of significant phases that the young, middle-aged and older adults had.

Based on section 5.3, For the minimalist shoes, soleus, gastrocnemius medialis, gastrocnemius lateralis and vastus lateralis had the same number of significant phases throughout the different ages. Thus the effect of the minimalist shoe is consistent on these muscles, across all ages. Even though the number of significant phases are constant for all age, the number of significant phases average at 3 out of 5 gait phases studies.

For tibialis anterior, vastus medialis and bicep femoris, the number of phases that had statistical differences ($P < 0.05$) increased with age. The effect of the minimalist shoe had more impact with these 3 muscles as progressed. On average 2 to 3 out of the 5 gait phases studies was significant.

However, the effect of the minimalist shoe as compared to the control shoe had a declining trend with the other muscles. Peroneus longus, rectus femoris, semitendinosus had a lower number of phases of significant differences as age increases.

Based on the results, it can be noted that minimalist shoe does have its uses for the middle-aged and older adults on the muscles, except for peroneus longus, rectus femoris, and semitendinosus, as 60% of the gait cycle is affected by the shoe.

T-test was conducted between the control shoe and the minimalist shoe for the three different age groups of adults. However, the gait profile of the muscles was inconsistent for all the age groups and hence the effect minimalist shoe was not reflected in the t-test.

The values from the IEMG gives a better indication of the muscle activities during the gait cycle. Different results were recorded from this test as the force exerted by each individual while they walk are different. This also provides a clearer indication of the muscle that exerts the most force.

The soleus, gastrocnemius medialis, rectus femoris, vastus medialis and gastrocnemius lateralis were consistent throughout the different age group. Whereas, the muscle activities for vastus lateralis, bicep femoris and tibialis anterior increases with the age of the subjects.

Comparing the effects of minimalist shoe to that of the control shoe, the minimalist shoe has a lower muscle activity than the control shoe. There is a

significant decrease in the muscle activity for gastrocnemius medialis, tibialis anterior, and peroneus longus when minimalist shoe is worn.

Therefore, minimalist shoe can be used on middle-aged and older adults as less force needed for walking.

5.10.2 Multiple density sole

The P-values for the two t-test done showed similarities in most of the muscles studied except for soleus and semitendinosus.

When the normalised amplitude of the soleus muscle is being tested, it had 2 phases of statistical significant ($P < 0.05$) differences for all age group, however when the area is being compared, the young and middle-aged subjects had 3 phases of differences while the older adults had 5 phases of statistical differences ($P < 0.05$). Even though the older adults had 5 phases of significant differences when comparing the P value, when comparing absolute area of the muscle activities with control as 100% (Table 4-6), the older adults did not have any significant changes in the muscle activities.

When comparing the normalised amplitude, the semitendinosus muscle had 3 phases of significant differences for the young, but when compared with the IEMG method, it had 5 significant different phases. The absolute value of the area is compared and the results supported the p-value for the area. All 5 phases had significant differences in area as compared to the control shoe. The number of significant phases decreased with age for the muscle, from 5 to 3.

For the rest of the 8 muscles, the trend for the number of phases of significant difference decreased as age increased. Based on the results, FitFlop, will have little impact or no difference from a normal shoe for most of the muscle measured in this experiment. Only 20% to 30% of the gait cycle will be affected by FitFlop for the middle-aged and older adults, with the exception of the semitendinosus muscle. The result supports the past study done, where overall muscle activity of bicep femoris and gastrocnemius medialis were reported to have insignificant changes for the older population [10].

A T-test was conducted between the control and fitflop shoe with gastrocnemius medialis, gastrocnemius lateralis and peroneus longus that has significant differences in the middle and older aged adults. While for the young subjects, it showed an approximately close relationship except for vastus medialis.

It can be concluded that based on intra-subject IEMG comparison that, popular midsole and outsole footwear features have a localized effect only on major calf and shin muscles, but not on other key lower-extremity gait muscles. The study also points out the effect of comparison methodology based on contrasting results between intra-and inter-subject comparison.

5.10.3 Rocker bottom sole

Based on these seven muscles, soleus, gastrocnemius lateralis, peroneus longus, vastus lateralis, rectus femoris, semitendinosus and bicep femoris showed a decrease in the number of significant phase as the subjects' age increase. The

number of phases of significant differences for the older subject range for 0 to 2 as compared to the young subjects' 3 to 4.

For gastrocnemius medialis and vastus medialis muscle the average number of significant phases remains the same, at 3, for all age group.

More significantly for the MBTTM shoe, the number of significant phases for the tibialis anterior increases with age. The older adults have 5 significant phases for the muscle as compared to the young and middle-aged subject whom have averaged 3 significant phases.

The MBT had minimal impact or differences for the middle-aged and older adults for most muscles. However, three muscles, gastrocnemius medialis, vastus medialis and tibialis anterior, had significant differences as compared to the control shoe during at least 60% of the gait cycle. This result coincides with a study done previously by Nigg et al. that reported the increase in muscle activity for the same muscles [8].

CHAPTER 6 CONCLUSION AND FUTURE WORK

6.1 CONCLUSION

The following hypotheses were confirmed:

- Based on results presented in section 5.1 it can be inferred that leg-dominance effect was present in the lower extremity muscles
- Based on the results presented in section 5.3 and 5.4, it can be established that age-related differences were observed in the lower-extremity gait muscle activity among young, middle-aged and older adults. Midsole and outsole footwear features affect lower-extremity muscle activity differently across age-groups.
- Inferences directly drawn from section 5.3 and 5.4 also enables us to conclude that different SEMG data analysis methodologies have varied effect on the results obtained: Amplitude analysis versus Integrated EMG analysis, Intra-subject versus Inter-subject differences.

Three shoes were identified for experiment, Adidas Adipure Trainer 1.1, FitFlop and MBTTM, to compare the differences between them with a control shoe used as a reference. An entire gait cycle is being breakdown into 5 phases and further analysed. A total of 10 muscles are studied in this experiment. Two T-tests were used to determine the statistical differences ($P < 0.05$) between the shoes and the control shoe. The first t-test analysed the normalised amplitude of the gait cycle

and the second t-test analysed the IEMG values, which it is in relation the work done by the muscle.

The t-tests comparison between the minimalist shoe showed positive results ($P < 0.05$) for middle-aged and older adults. 60% of the gait cycles of 7 muscles are affected by the minimalist shoe.

The comparison for the middle-aged and older adults between the FitFlop and the control shoe showed minimal significant difference between the 2 t-tests ($P < 0.05$). Only 20 to 30% of the gait cycle is affected by the FitFlop shoe.

The comparison between the MBTTM and the control shoe showed minimal differences for seven muscles for the middle-aged and older adults. However, three muscles exhibited substantial difference from the control shoe and supported previous studies done.

Out of the footwear feature studies it can be inferred that inter-subject findings showed that MBTTM rocker bottom shoe had a greater effect on older adults than other age groups. FitFlopTM multiple density type did not significantly differ on all the observed age groups. Among the footwear types compared, Adidas Adipure TrainerTM minimalist-type exhibited the most significant difference in all age groups.

It can be concluded that based on intra-subject iEMG comparison, popular midsole and outsole footwear features have a localized effect only on major calf and shin muscles but not on other key lower-extremity gait muscles. The study

also points out the effect of comparison methodology based on contrasting results between intra-and inter-subject comparison.

6.2 Contributions

The impact of exercise footwear features in middle-aged and older adults has been barely addressed by the scientific community. Evidence suggests that midsole and outsole features affect gait muscle activity, but primarily focussing on a younger-age group [23-29]. This project's approach quantified and compared the effect of midsole and outsole features on middle-aged and older adults against a younger age group. The contributions of the project can be summarised as

5. In-depth and rigorous SEMG based comparison of gait muscle activity on ten key lower extremity muscles on various midsole and outsole features during a gait cycle.
6. Analysing the effect of age-related changes in the lower extremity gait muscle activity and the influence of midsole and outsole footwear features on the above.
7. The EMG methodology routinely involved averaging of the muscle activity across all subjects or a muscle or an age-group into one representative dataset. Then, comparing, analyzing and drawing conclusions based on the representative dataset, which could lead to

differences in inferences concluded [1-5]. This project rigorously compared the effect of difference SEMG methodologies including subject variability and method variability. The results highlighted the effect of SEMG method and concluded that the differences observed could be affected by the method and subject conditions. The impact of these differences would enable future SEMG-based footwear studies to consider an intra-subject approach rather than an inter-subject comparison.

8. A review-based scoring system was developed for additive manufacturing techniques was done to suggest faster prototyping of footwear features in the future.

The following articles were accepted/published:

- EMG-based comparison of intra- and inter-subject variation in lower extremity gait muscle activity for various footwear types, V Manoharan, SM Chou, G Chai, S Forrester and P Kong accepted in 2nd International Conference in Sports Science & Technology, Singapore, 2016.
- Effect of popular exercise footwear on the gait muscle activity of middle - aged and older adults: preliminary findings, V Manoharan, SM Chou, G Chai, S Forrester and P Kong in 1st International Conference in Sports Science & Technology, Singapore, 2014.
- Application of additive manufacturing techniques in sports footwear. V Manoharan, SM Chou, S Forrester, GB Chai - Virtual and Physical Prototyping, 2013.

6.3 Limitations

Butterworth band-pass filter with corner frequency of 10 – 500 Hz [54] to eliminate artifacts, crosstalk and other noises which are usually of extreme low and high spatial frequency. The filtered data will then be full-wave rectified to convert negative voltage values to positive.

Strict exclusion criteria based on Dynamic Gait Index (DGI) Scale was followed in selection of subjects prior to the experiments to minimize variability.

Lifestyle, exercise and other factors are noted to affect muscle health. However, the focus of this research is to quantify muscle activity differences as age-progresses assuming all subjects are normal and healthy.

The comparisons were based on a standard 100% gait cycle and normalized amplitude, for it was noted in literature review to reflect muscle strength and linearly correspond with force. Activation times, synergy and co-activation were not studied as part of the hypothesis testing for it was not a direct indicator.

As noted in section 5.1, initial experiments to study leg dominance, gastrocnemius muscle activity was used as a reference to identify start and end of gait cycle. Gastrocnemius on/off signal is distinct and consistent and therefore can be used in this case. The “problem” is effectively resolved by using the gastrocnemius muscle activity. The paragraph in section 5.1 has been rephrased to improve

clarity. The identifying of gait cycle issue was only noted during the first hypothesis testing only.

Literature reviewed as indicative in table 2-2 uses different filters and SEMG protocol methods hence a direct comparison is relevant.

T-test was considered for hypothesis testing. Owing to the high frequency content inherent to an SEMG signal, the values obtained and evaluated are normalized and averaged in to 100% of the gait cycle i.e. 100 representative data points across 5 phases. Hence, the comparison was only done between a control condition versus the testing condition to confirm or nullify hypothesis. Hence a simpler paired and unpaired t-test was used according to the condition compared.

Gait kinematics was not measured. As indicated in page number 23 – “Kinematics of lower extremity joints are sometimes measured through motion analysis cameras to analyze gait [58]. However, kinematic movement and kinetics of a particular joint is controlled by more than one muscle, overlapping or compensatory muscle activity might occur in executing a kinematic event, therefore analyzing kinematics of gait cycle may not directly reflect the extent of muscle activity during gait [58]. Plantar only indirectly reflects muscle activity or correlates with muscle health deterioration. Thereby, a more direct approach for measuring muscle health and activity is preferred.”

6.4 Future work

It can be noted footwear conditions studied had different effect on various age-groups, thus it can be inferred that age has a significant effect on exercise footwear condition of lower extremity muscle activity.

Future work would include increasing the sample size of the age groups and comparing more footwear conditions thereby comprehensively understanding the effect of different exercise footwear types on age-groups. Also we could consider a medio-lateral based multiple density based footwear design. A faster prototyping method would enable a faster design process thereby more robust experimentation and faster footwear based studies.

Additive manufacturing (AM) techniques can be utilised in faster designing and manufacturing of whole footwear prototypes or individual parts. It also gives flexibility in design, customization and manufacturing personalised footwear and parts like insoles, etc. Personalization enables improved fit, performance, reduced risk of injury and serves other pathological conditions.

The following sections seeks to review and explore AM techniques that are being utilized in the manufacturing of sports footwear. A five-point scoring technique based on the four aspects namely accuracy, surface finish, materials supported and building/processing speed was devised to evaluate the various AM techniques for footwear.

6.4.1 Stereolithography (SL)

SL technique involves usage of photo-curable resin medium that photo-polymerizes when exposed to laser [162]. The photo-polymerized resins were noted to exhibit Young's modulus from 25 MPa to 1500 MPa [163], which can be relevant for sports footwear and parts. SL technique is also being used to create shoe last design based on anthropometric data [164, 165]. Key advantages of SL technique would include good dimensional accuracy within ± 0.1 mm, best surface finish of all AM techniques [162, 166]. Drawbacks of this technique include time taken for post-curing, requirement of support structures and restriction of materials used (only photo-sensitive resins) [162, 166].

6.4.2 PolyJet™ (PJ)

PolyJet (PJ) technology prints and photo-polymerises parts layer by layer like a typical inkjet printer [162]. Chua et al. have noted that Adidas–Salomon AG used PolyJet™ technology for design verification, development and production tooling. Footwear prototypes were reproduced within a short span of time from relevant CAD file [162]. In a survey, PJ technology was the second most preferred technique (17%) among AM service providers [167]. Key advantages of this technique compared with SL would include relatively higher accuracy, wider range of materials, faster processing speed [162]. Drawbacks are relatively poorer surface finish compared to SL and the need of water jet to wash off any additional material left in the processing phase. This also lead to wastage of materials [162].

6.4.3 Laser sintering (LS)

This is a powder based AM technique that is characterised by deposition of powder layer by layer and then using CO₂ laser to fuse the powder, repeating the process until the indicated 3D solid prototype is created [162]. In a survey by Wohler [6], AM service providers indicated LS to be their preferred technique. Advantages noted by Chua et al. [162] include the use of wide range of processing materials like nylon, polycarbonates, metals and ceramics compared to photo polymers mentioned in the previous two techniques, no need of support structures unlike previous techniques, etc. Drawbacks of this process include poor surface finish, relatively large size of the printing unit, high power consumption and lower density of the resultant material owing to the use of powder [162, 166]

In Vinet and Caine's article [168] on sprint footwear, they noted that laser sintered nylon-12 sole 'compared favourably' to other commercially available sprint soles during traction tests. Toon et al. [169] used LS technique to manufacture variants of the same footwear with varying bending stiffness to assess the effect of footwear stiffness on human performance. Salles and Gyi [9] reported that the approximate time required for fabricating six pairs of insoles using LS was 28 hours [169].

6.4.4 Z Corporation's Three-Dimensional Printing (3DP)

This technology involves deposition of powder layer by layer and then addition of binder solution on the powder [162]. Chua et al. reported that notable footwear companies like Adidas, New Balance and Wolverine used 3DP in their prototype

development.

Advantages of this technique would include the usage of high performance composite materials, printing of coloured parts, higher speed of printing and minimal wastage of materials [162]. Drawbacks would be poor surface finish and weaker functional parts [162].

Scoring – AM techniques in sports footwear

For the previously identified AM techniques, a five-point scoring system was used for four important aspects (5 indicating best performance in the aspect) relevant to sports footwear. The score is tabulated in table 7-1.

Table 6-1. Five-point scoring of AM techniques on aspects relevant to sports footwear

AM technique	Accuracy (Max 5)	Surface finish (Max 5)	Materials supported (Max 5)	Build/Process speed (Max 5)
Stereolithography (SL)	2	5	2	4
PolyJet™ (PJ)	3	4	2	4
Laser sintering (LS)	4	3	4	3
Z Corporation's Three-Dimensional Printing (3DP)	5	3	5	5

Based on the above scoring table, it can be inferred that LS and 3DP techniques have advantages in accuracy and range of materials supported but lack in surface finish. SL and PJ techniques have advantages over speed and surface finish but not in the range of materials supported. Overall 3DP has many advantages over the other techniques with the fastest build time.

6.4.5 Personalised footwear design and studies

Customization of sports footwear based on individual anthropometry and pathological conditions offers many benefits including reduced risk of injury, improvement of performance, comfort, fit and support offered by footwear. Salles et al. [169] identified five potential elements in an AM-based footwear personalization methodology, they are discussed as follows:

1. **Foot profile capture**– Involves capture of 3D foot profile using a foot scanner or other imaging techniques [169]. This data was used for customising the footwear design for an individual's foot profile.
2. **Anthropometric measurements** – Calculating anthropometric data of the foot based on anatomical landmarks like arch height, height at the midfoot and forefoot, etc. [169]. Anthropometric data along with 3D scan data can be used in more precise and accurate representation of the foot model.
3. **Insole design using CAD software** – based on the data obtained from scan data and anthropometric measurements, a 3D model of the foot was constructed. Use of relevant software to design the footwear or footwear part on the 3D model will make the design file compatible with relevant AM technique.
4. **Manufacture of the parts using AM technology** – The CAD design file format from the previous method was built layer by layer through additive manufacturing approach. The footwear can be built entirely or in parts [169].

5. **Physical/biomechanical examination** – On the AM built part, physical and biomechanical performance like comfort, fit, etc. can be evaluated with the help of professional evaluators like physiotherapist, podiatrist, etc.. Effects on human performance can be verified through human trials, variables like plantar pressure, peak pressure, rearfoot pronation, tibial internal rotation, peak vertical impact etc can be measured [169]. Other properties including bending stiffness etc. can also be examined [169].

Salles et al. [169] compared AM-based personalised insole against a standard commercially available insole. Overall, no significant difference was found between the conditions on discomfort, lower extremity biomechanical parameters (plantar pressure distribution, ankle joint angles (tibial internal rotation and rearfoot eversion) and vertical ground reaction force.

6.4.6 **Challenges facing use of AM techniques in sports footwear industry**

Key challenges noted by Wohler [167] are relevant to the use of AM in the sports footwear industry; they are material development, pricing, old design habits, cultural problems and low profit margins. However, in sports footwear industry, AM techniques are still practical for faster prototype development and customisation despite the indicated commercial challenges. Stereolithography, PolyJet™, Laser Sintering, Z Corporation's Three-Dimensional Printing and Laminated Object Manufacturing are identified as relevant AM techniques that can be potentially used in the sports footwear.

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APPENDIX 1.1

Atlas of lower extremity human musculature

APPENDIX 1.2

Barefoot-Middle

Barefoot-Old

Control-Young

Control-middle

Control-Old

Fitflop-Young