Electromyography Study on Lower Limb Muscle Synchronizations Strategies during Walking and Sit-to-Stand Tasks on High-Heeled Shoes

A Dissertation submitted for

The partial fulfillment of

Master of Engineering Research

By

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as part of the collaborative doctoral degree and fully acknowledged within the text.

I also certify that I have written the thesis. Any help that I have received in my research work and the preparation of the dissertation itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

High-heeled shoes as accessories are prominent in today’s society. They are worn on special occasions as well as with casual outfits. Specific muscle activation and synchronization changes occur when performing Sit-to-stand and walking tasks in shoes with high heels vs. lower heels. The reformed demands on muscles mostly accompanying the muscle synchronization changes have not been well documented. As walking and sit-to-stand while wearing HHS in the work environment is very common for professional women, it is essential to understand the health implications. Therefore, the main purpose of this study is to identify changes in muscle activation and synchronization patterns when Sit-to-stand and walking are executed in high-heeled vs. low-heeled shoes.

Between 10 and 15 Healthy young women participated in the study. Participants performed two tasks - sit to stand and walking. Both these tasks were performed in different experiment sessions, where each participant was made to wear heeled shoes of different heights (4cm, 6cm, 8cm and 10cm for walking task and 4cm, 6cm and 10cm for STS task). Muscle activities from the dominant leg were recorded. The investigated muscles were: Rectus Femoris (RF), Vastus Lateralis (VL), Vastus Medialis (VL), Semitendinosus (ST), Tibialis Anterior(TA) and Gastrocnemius (GA). RMS analysis of all muscles, Co-contraction analysis of RF – ST, VL – ST and VM – ST and combinations and coherence analysis of RF-VL, RF-VM, and RF-ST combinations were carried out.

When comparing parameters relevant to different heel heights, a significant increase in muscle activity was perceived in all muscles involved in the two tasks. Co-contraction and Coherence parameters were increased in all three muscle pairs in both tasks. An interesting observation made was that irrespective of heel heights, the percentage contribution of muscle activation and percentage contribution of muscle pair synchronization remain same in sit-to-stand and walking task.

These results reflect greater alteration demands for joint stability, balance and avoid from falling during sit-to-stand and walking in shoes with increased heel height.

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Chapter 1 : Introduction

1.1 Outline

This chapter aims at presenting the thesis outline and briefing of research outcomes, which is done during Master by Research Degree. The first section summarizes the research background and previous studies performed in the chosen domain of investigation, which includes research gap. The next section emphasizes the research hypothesis formulation, aim, objectives and the thesis statement. Following sections also enlists the unique contributions in research concepts and publications as well as the thesis organization.

1.2 Research Domain

1.2.1 Background

In all over the world, the use of high-heeled shoes is very common for various purposes. High-heeled footwear was part of traditional cultures for centuries. The ancient Egyptians had them as a prominent accessory in their cultural outfits, as per documentation from around 4000 B.C. This practice is considered to be the predecessors of today´s high-heeled footwear (Paslawsky 2008).

Later towards the modern times, emperors in the Chinese kingdoms appeared to have worn tall heels to take up a taller appearance. In European Victorian and Elizabethan eras, women with long hem gowns and dress wear had constantly used high heels to protect their gown hems from getting dirty on the ground (Thorpe 2016).

Today's modern societies have an iconic women's appearance described in sleek, classy outfits, fair amounts of make-up and accessories, accompanied by stylish high-heeled shoes. Women who dress-up so pride on a better appearance, since the legs now appear longer and slimmer – even a much-desired look from the male point-of-view.

Given the unusual position the ankle and foot are kept in when wearing high-heeled shoes, it is improbable that people with sound knowledge of the human musculoskeletal system would recommend wearing them. Despite that, they are trendy amongst women, both as a part of casual and dressy outfits.

As wearing HHS in the working environment is very common for women, it is important to know the problems it causes. Walking and Sit-to-Stand (STS) task is two most common activities of daily living. Millions of women in Western societies frequently perform Walking and STS task in High-heeled shoes (Bolink et al. 2012; Dehail et al. 2007; Linder & Saltzman 1998; Smith & Helms 1999; Williams & Haines 2014)

1.2.2 Context of study

The context of this research is to view and contribute towards solving a common problem in adult women - to avoid falling, imbalance and instability during daily activities of the human body that brings about changes in the locomotor system. These activities like walking at a normal pace or changing from sitting to standing position prompt certain known kinematic changes in the lower limb. These changes escalate under stressful situations like when walking in high-heeled shoes.

Along the sagittal plane, knee flexion is greater in high-heeled gait when compared to low-heeled gait. Hip flexion is also relatively less in magnitude when walking in high heels (Opila-Correia 1990b). However, changes in muscle activation pattern under the above-mentioned conditions have not been well documented by medical science or biomedical engineering research.

1.2.3 Definitions

The following terms and definitions were used for the present study:

1. High-Heeled Shoes (HHS):

   Footwear designed for women that has a stiletto (pointed heel) heel, which significantly raises the heel of the participant's foot higher than the forefoot.
2. Posture:

   A position of the body or body parts while in an activity like sit-to-stand and walking.
3. Healthy participant:

   A participant with no previous history of neuromuscular and musculoskeletal injury.
4. Co-contraction:

   Simultaneous activation of antagonistic muscles, which reflects on the strength of muscle-pair synchronization.
5. Coherence:

   It is the similarity between two signals, in this research two EMG signals, which can be related to the Common Neural oscillations during muscle activations.
6. Self-selected speed:

   A speed of walking which participants choose to minimize the stress, balance and maximize the comforts.

1.2.4 Problem domain

Various studies have been carried out to study the effect of HHS regarding Biomechanics, kinematics and so forth, as well as health issues like back pain, ankle twisting, and osteoarthritis. Usage of HHS causes the human lower-limb muscle system to adapt to maintain body-balance, through internal or external coordination.

Two approaches can be deliberated for measuring such adaptations - to identify or measure on the basis of individual muscles or muscle-combinations.

Significant studies have explored individual or paired muscle analysis, in day-to-day activities like walking and running. However, for the most frequent tasks while wearing HHS – Walking & STS have not been studied for Muscular adaptation patterns leading to balance maintenance. If done, it will uncover the behavior of entire muscle system in combination.

There are very few studies conducted on changes in lower-limb muscle activation patterns during HHS walking and STS tasks – using muscle pairs and not combinations. The purpose of this research is to inspect the patterns of muscle adaptation in the following muscle combinations:

- RF, VM, VL, ST, TA and GA Muscles
- RF-ST, VM-ST, and VL-ST muscle pairs
- RF-VM, RF-VL, RF-ST muscle pairs

1.2.5 Research Gap

It is essential to understand the effects of wearing HHS during walking and STS tasks on postural changes and muscle activations, as explained in the previous section. Wearing HHS during STS and Walking Task affects the strength of muscle pair coordination. Any health issues derived from this habit will help to understand muscle activation and coordination patterns, in terms of treatment strategies.

The proposed experimentation investigates muscle activation and synchronization pattern changes, during STS and Walking tasks while wearing High-heeled shoes, by:

- Applying RMS analysis on RF, VM, VL, ST, TA and GA Muscles
- Applying Co-contraction analysis on RF-ST, VM-ST, and VL-ST muscle pairs.
- Applying Coherence analysis on RF-VM, RF-VL, RF-ST muscle pairs.

1.3 Research Hypothesis Formulation

1.3.1 Research Aim

Aim 1: To investigate variations in lower limb-muscle activation-patterns (RF, VL, VM, ST, TA, and GA) in women during STS and walking tasks, for different heel heights.

Aim2: To analyze whether wearing high-heeled shoes affects the strength and pattern of antagonistic muscle pair synchronization.

Aim3: This study aims at identifying changes in synergistic lower limb muscle pair synchronization during STS and walking in different HHS.

1.3.2 Research Objective

Objective1: Computation and analysis of the contribution of muscle parameters (RMS) during STS and Walking tasks, executed by a person wearing high heels.

Objective 2: Computation & Comparison of Co-contraction indices of three separate, antagonistic muscle pairs (RF-ST, VL-ST, and VM-ST) among different heel heights for STS and walking task.

Objective 3: Computation & Comparison of Coherence indices of three separate synergetic muscle pairs (RF-VL, RF-VM and RF-ST) were compared, among different heel heights for STS and walking task.

1.3.3 Research Hypothesis

1. Based on RMS analysis on the selected six pairs of muscles:

- Irrespective of the task involved in, lower limb muscle activity increases with elevated heel height.
- Irrespective of heel height in use, muscle utilization factor remains constant during walking and STS.

2. Based on Co-contraction analysis on the selected three pairs of muscles:

- Irrespective of task, co-contraction would be significantly higher in high-heeled shoes
- Irrespective of heel height, CCI distribution of all three antagonistic muscle pair remains same in two different tasks.

3. Based on Coherence analysis on the selected three pairs of muscles:

- Irrespective of the task, Coherence value would be significantly higher in women using high-heeled shoes.

4. Thesis Statement

Regardless of the Task performed (Walking and STS), lower limb muscle activity increases while wearing high-heeled shoes, with muscle pair synchronization pattern being maintained constant by their compensation strategy.

1.3.5 Scope of Research

The proposed research has potential in various biomedical problems. High heels, which is now an integral part of the female lifestyle in modern society, will find its way to footwear in Prosthetic limbs for women. The professional and social impact of such a device has been well proven (Clark 2016). The findings in this thesis will help to understand the mechanics behind design and production of advanced Prosthetics.

This study will also help in creating an impact on physically impaired women. Any situation, where neural strategies and muscle synchronization patterns are required for further diagnosis and treatment or even research purposes, can benefit from these findings. Health applications such as stroke rehabilitation & pregnancy monitoring also rely on such concepts - neural strategies and muscle synchronization patterns - to ensure stability and balance around a joint, during daily activities.

1.4 Research Outcomes during period of study

This research has following outcomes

- Irrespective of the task, lower limb muscle activation pattern remains constant in all heel height by increase the muscle activity.
  This fact is verified through an RMS analysis procedure.
- Irrespective of the task, the strength of antagonistic muscle pair synchronization pattern or their strength of coordination pattern remain same in all heel height by increasing their strength of coordination.
  This statement is shown by an analysis of the Co-contraction ratio.
- Irrespective of the task, common drive to synergistic muscle pair increase with elevated high heel shoes.
  This point is demonstrated by analyzing the Coherence of muscle pairs through the investigation of EMG signals.

The proposed study evidence and interpretations are conducted on a short-term time scale. Based on these outcomes, it is inferred that the lower limb muscles have the ability to adjust with external-environment changes during a Walking and STS task on HHS to prevent falling and imbalance. These adjustments are the higher muscle activity, enhanced the strength of muscle pair synchronization and increased common neural oscillation.

1.5 Novel Research Contribution

The following are contributions by this research:

- EMG data collection from a tailored test subject sample set, for STS and Walking Task while wearing High Heeled Shoes.
- Experiment Design based on a new problem-solving approach for analyzing selected parameter behavior for the two activities.
- Computation of RMS, Co-contraction and coherence parameters for lower limb muscles during walking and STS task while wearing HHS.
- Finding of Muscle activation pattern and muscle pair synchronization Pattern while performing walking and STS task with High heel shoes.
- Relevant Research Publication

1.6 Publications during Research

1. Naik GR, Pratihast M, Chai R, Al-Ani A, Acharyya A, Nguyen HT "Differences in lower limb muscle activation patterns during Sit to Stand Task for different heel heights." In: 2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), 11-15 July 2017 2017. pp 2486-2489. doi:10.1109/EMBC.2017.8037361

2. Ganesh R. Naik, Manisha Pratihast, Ahmed Al-Ani, Rifai Chai and Hung T. Nguyen "Compensatory strategies during sit to stand task in response to excessive muscle co-contraction during high-heeled gait" (Submitted to Biomedical Engineering Online)

3. Manisha Pratihast, Ahmed Al-Ani, Rifai Chai, Steven Su and Ganesh Naik "Changes in lower limb muscle synchronization during walking on high-heeled shoes" (Accepted to Healthcare Technology Letters)

1.7 Thesis Organisation

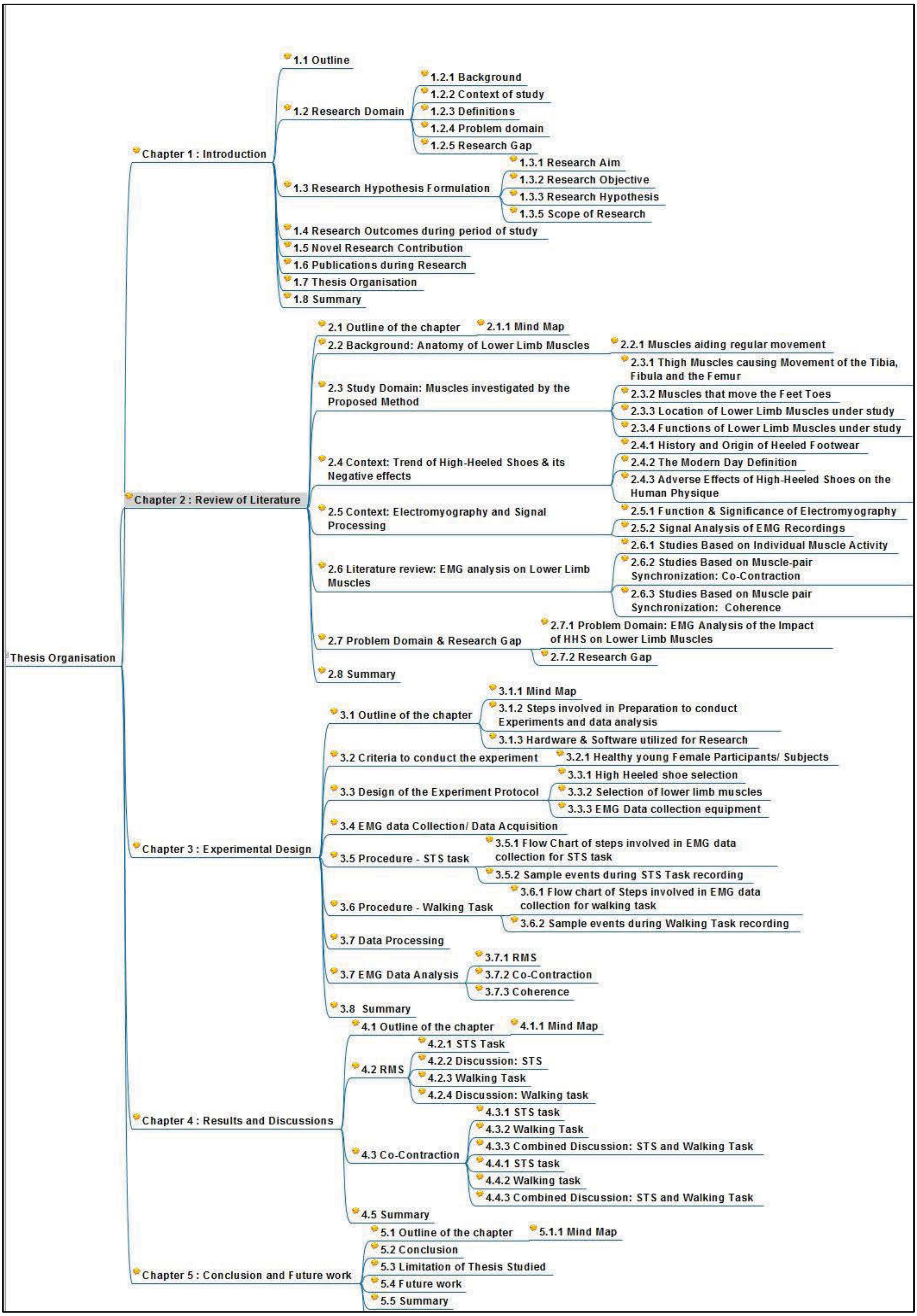


Figure 1.1 Thesis Organization

1.8 Summary

This chapter gave the outline of all chapters in this thesis. Also explored the background, problem domain, context of the study, research hypothesis formulation, learning outcomes and novel contributions to research.

Chapter 2 : **Background and Literature**

2.1 Outline of the chapter

This chapter aims to present background information and a literature review relevant to the research problem investigated and the proposed solution of this thesis.

The first section investigates the structure and anatomy of lower limb muscles, highlighting those features relevant to the experimentation & discussion within the scope of this thesis.

In the second section, the importance of the high-heeled shoes and argumentative effects of habitual high-heeled shoe use are explored. Popular examples include the effects on the trunk, hips, knee, ankle and foot biomechanics. Background on Electromyography and signal processing are structured in the following section, directing through the process of EMG data collection and data analysis.

The last section presnts a deeper review of the literature and problem domain. Which includes muscle activity individually and in pairs, based on synchronization measured through Co-contraction and coherence analysis. This chapter provides the frame for interpretation and discussion of the experimental results.

2.1.1 Mind Map

Below is the mind map of this chapter.

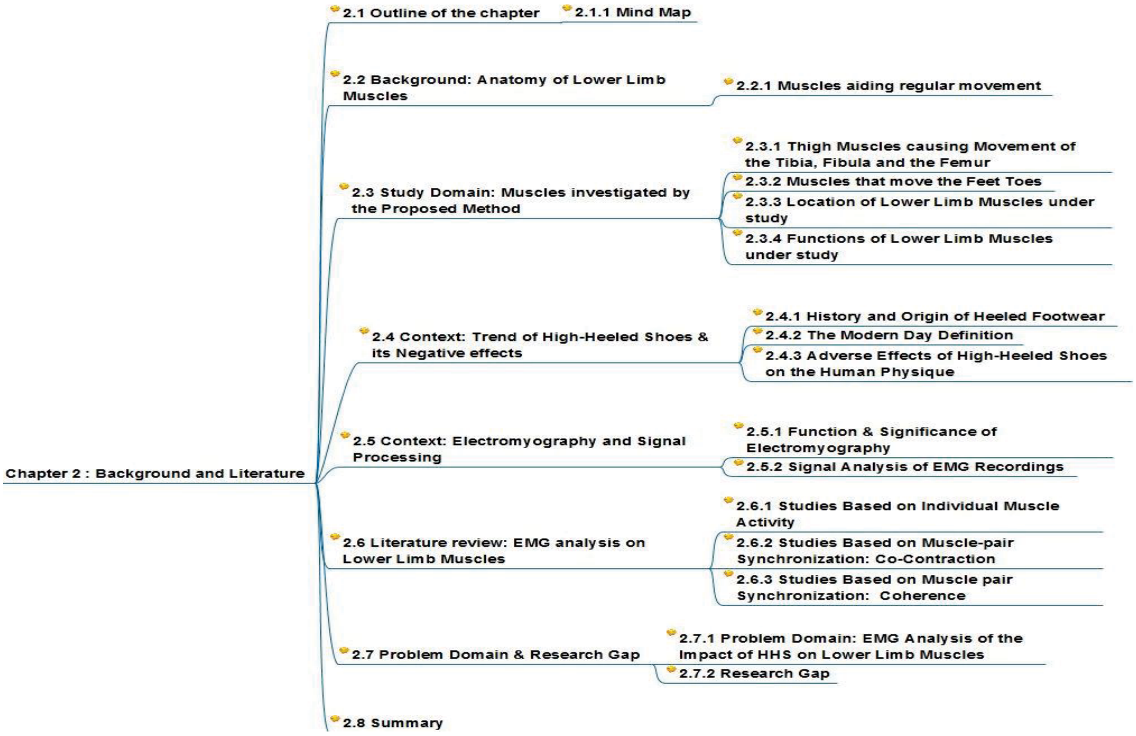


Figure 2.1 Review of Literature

2.2 Background: Anatomy of Lower Limb Muscles

The lower limbs in humans are generally called legs and originate from the pelvis or hip girdle (Levangie & Norkin 2011). Their main functions are:

- Support the body weight that is channeled through the hips and conveys the pressure to the ground for stable posture.
- Execute coordinated muscle activity to produce movements like walk, sit, stand, crawl, jump and bend.
- To support and propel the mass of the physique in required directions, and ensure body balance.

As in every other anatomical region, the lower limbs are also entrenched with the human circulatory system (blood vessels), the nervous system (locomotor nerves) and the endocrine system, which are all involved in the coordinated limb functioning. The lower limbs are covered in the following six regions:

- ***Buttock or gluteal region*** is the transition between the trunk and the lower limbs. It lies behind the pelvis, extending from beneath waist (iliac crest region) to the buttock fold (posterior horizontal crease-line along the fold of the hips). It is the point of emergence of muscles, nerves & vessels towards the lower limbs. The muscles here are the gluteas (maximus, medius, and minimus), the deep located piriformis, obturator internus, gemellus muscles, and the quadratus femoris.
- ***Thigh or femoral region*** is the upper region of the lower limbs, between the hips and the knee region distally, largely composed of the femur or thigh bone and femur muscles.
- ***Knee or knee region*** includes the distal femur and proximal tibia, fibula head, patella or kneecap, and the associated joints.
- ***The Leg or Leg region*** is the part of the lower limb between the knee and the rounded medial and lateral bulges flanking the ankle joint. It constitutes the tibia (shin bone) and fibula, joining the knee and foot. The posterior prominent muscular structure is named the ***leg calf,*** made up of the triceps muscle, from which the Achilles tendons extend till the heel.
- ***The Ankle or talocrural region*** is marked by the malleoli (lateral ankle prominence), including the distal leg portion.
- ***Foot or foot region*** is the most distal lower limb area containing the tarsus, metatarsus, and phalanges (or toe bones), with the superior and the inferior, ground-contacting surfaces named

dorsum & sole or plantar region of the foot. Toes are the foot digits, with the great toe made of two phalanges and the other four of three phalanges each.

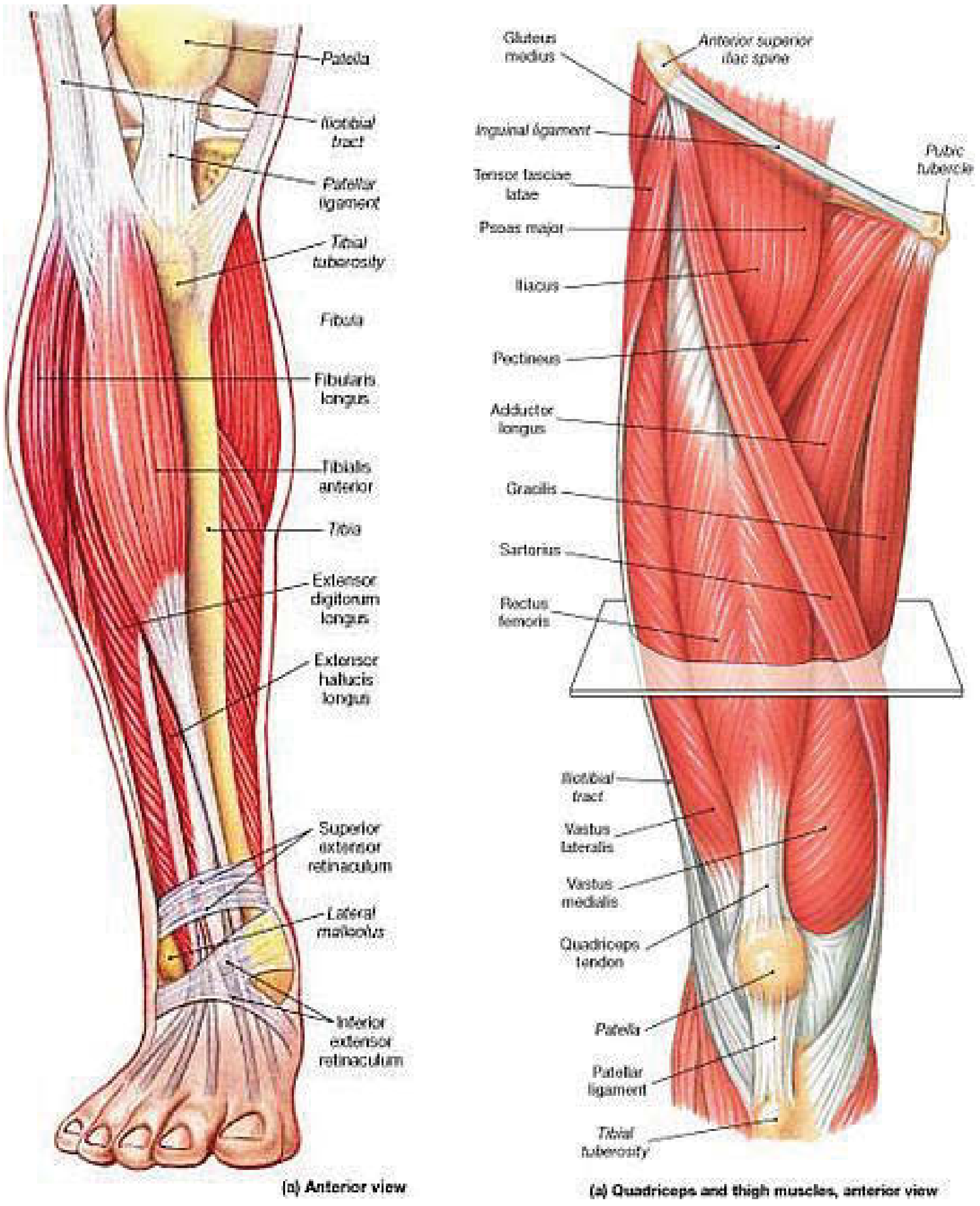


Figure 2.2 Superficial anatomy of the lower limb muscles (Levangie & Norkin 2011)

2.2.1 Muscles aiding regular movement

The two most common motions undertaken by an average human is regular paced walking and changing position from Sit-to-Stand. The lower limb movements in both these cases are initiated as a continuous reaction between the various sections of the lower limbs. It is initiated at the Hip Joint, formed by the femur bone and the pelvis acetabulum, in a ball-and-socket joint structure. The main motions of the limb during walking are as illustrated below in Figure 2.3, and the movements may be summarized as follows.

- Hip Flexion lifts the thigh upward in front of the trunk. The flexors muscles are rectus femoris, iliopsoas, sartorius, and tensor fasciae latae.
- Hip Extension from the regular erect position, the thigh is lifted behind through the extensor muscles or the hamstrings and gluteus maximus.
- Hip Abduction or leg lifts to the side, by abductors gluteus medius and minimus.
- Hip Adduction or lowering of the thigh to the erect anatomical position from the abduction position, using Adductor group.

The two main groups of muscles in action in this regard are:

- Hip Flexors or the Quadriceps – Rector Femoris (RF), Vastus Lateralis (VL), Vastus Medialis (VM) and Vastus Intermedius (the deeply embedded muscle).
- Hip Extensors or Hamstrings, in mass composed mainly by Semitendinosus (ST), Semimembranosus & Biceps Femoris.

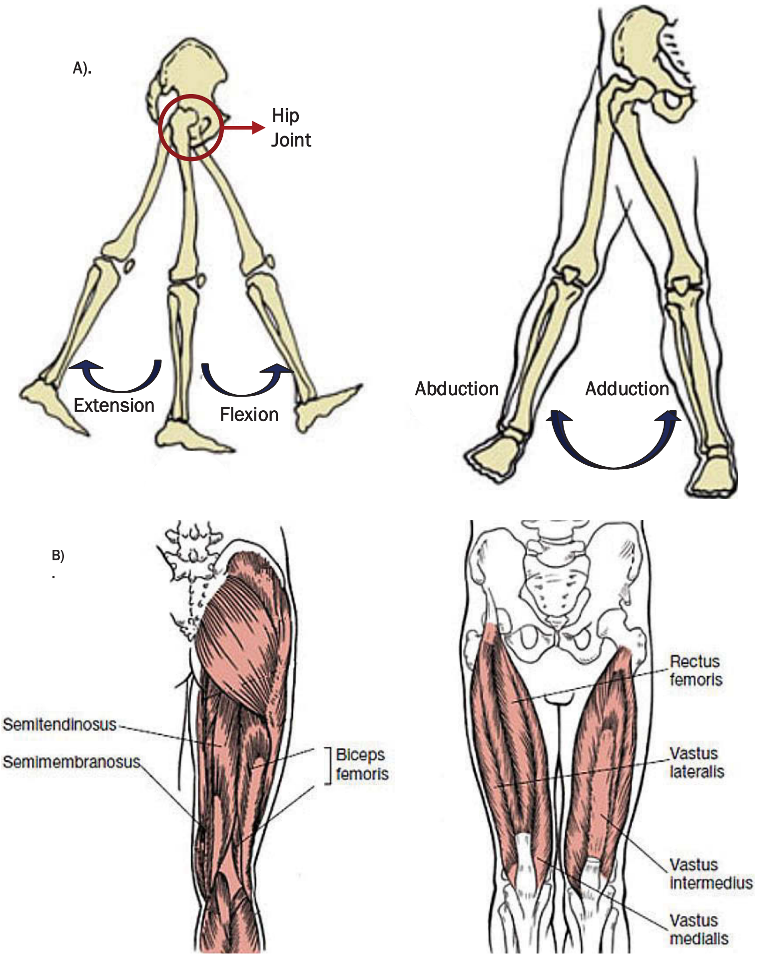


Figure 2.3 A). Muscle actions involved during the walking task, and B). The main muscles engaged (Levangie & Norkin 2011)

2.3 Study Domain: Muscles investigated by the Proposed Method

Out of the anatomical components of the lower limbs, for Surface-EMG analysis and corresponding interpretations, the superficially located muscles contribute the most to the Limb movement. Hence, they are the investigated muscles. The following subsections elaborate the structure and anatomy of these two muscle groups as the topics of our study:

2.3.1 Thigh Muscles causing Movement of the Tibia, Fibula and the Femur

There is three main compartments, which causes movement of the Femur, Tibia & Fibula - the anterior, medial and posterior compartments – separated from each other by Deep fascia muscles. Their primary function is to extend and stabilize the knee region, while under the external and internal stress of movement.

1. **Quadriceps Muscles:**

The anterior compartment of the thigh is made of the Quadriceps Femoris group, commonly called the Quadriceps muscles. Tendon binding this group is the quadriceps tendon (patellar tendon), by inserting into the patella, continuing below it into patellar ligament. This ligament attaches to tibial tuberosity (Levangie & Norkin 2011). This group of four muscles, their functions, and positions are below:

Rectus Femoris (RF) (anterior thigh aspect) moves the lower leg out in the front of the body in actions like forwarding stepping or kicking, and aids in assisting the knee. The origin is at the inferior anterior iliac spine along the superior margin of the acetabulum and inserts into the patella at the tuberosity of the tibia. It targets the Femur, tibia, and fibula to create tibia and fibula extension and thigh flexion (Levangie & Norkin 2011).

Vastus Lateralis (VL) (lateral thigh aspect) executes tibia and fibula intentions to move the lower body out to the front as in flexion. It originates along the intertrochanteric line at the linea aspera and culminates at the patella along tibial tuberosity (Levangie & Norkin 2011).

Vastus Medialis (VM) (medial thigh aspect) has its function, target, origin, and positioning are just like Vastus Lateralis, but doesn't start near the greater trochanter unlike the latter (Levangie & Norkin 2011).

Vastus Intermedius (VI) (between the Vastus Lateralis and Vastus Medialis, and is deep to the Rectus Femoris) functions like the Lateralis and Medialis muscles, emerging from the proximal femur shaft while converging at the same point as the other two (Levangie & Norkin 2011).

As three muscles RF, VL, and VM are responsible to stablise the knee joint and movement of the lower limb, they are chosen for this study.

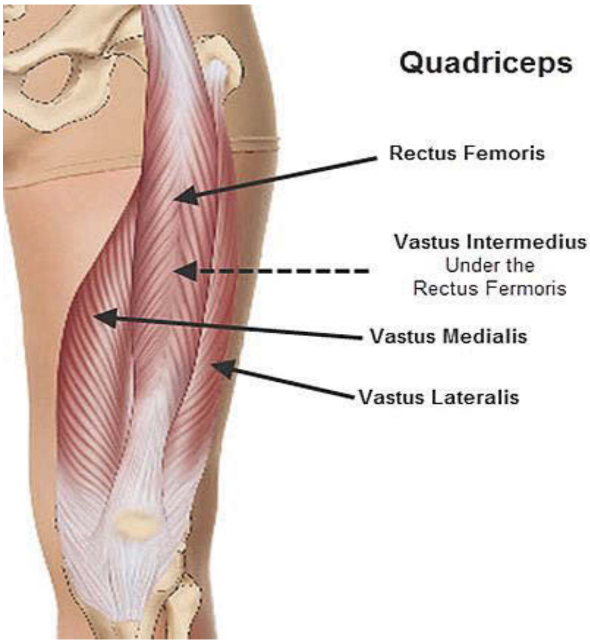


Figure 2.4 Muscles of the Quadriceps group (Levangie & Norkin 2011)

2. **Hamstrings Muscles:**

Hamstring Muscles are the class of three muscles located in the posterior compartment of the thigh. They are separated from the other two compartments by the Deep Fascia. Tendons connecting them form the popliteal fossa which is the diamond-shaped space behind the knee. Individually, their location, role, and placement are discussed below:

Semitendinosus (ST) work towards the moving back of the lower legs up and backward to the buttocks. They also push the thigh down backward, and twists the thigh and lower extremity outwards (Levangie & Norkin 2011).

Semimembranosus (SM) moves the lower leg back region upwards towards the buttocks while moving the thighs back downwards and twists the lower leg inwards (Levangie & Norkin 2011).

Biceps Femoris (BF) moves the back of the lower leg region upwards and backward to the buttocks, while the thighs backward and downward and twists the thigh inwards (Levangie & Norkin 2011).

As the prominent displacement of the lower extremity is contributed by the Semitendinosus (ST) muscle, it has been considered from this set for our study.

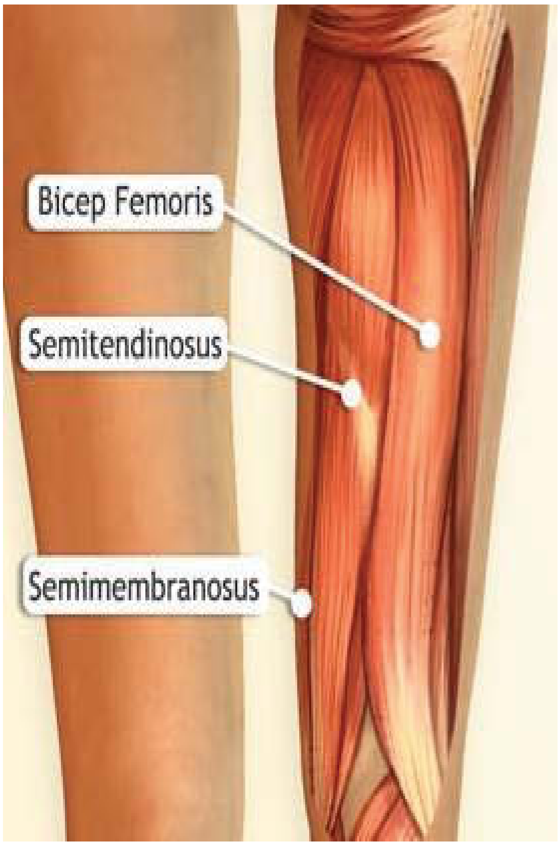


Figure 2.5 Hamstring Muscles(Levangie & Norkin 2011)

2.3.2 Muscles that move the Feet Toes

The lower extremity muscles are also divided into three compartments namely anterior, medial and posterior – divided by the deep fascia muscles. The anterior compartment implements dorsiflexion, while the posterior compartment generates plantar flexion.

The lateral compartment made up of the Fibularis Longus and the Fibularis Brevis are deeply located, performing plantar flexion and eversion (Levangie & Norkin 2011).

1. **Anterior compartment of the Lower Extremity**

   Tibialis Anterior Muscle (TA) is the anterior compartment's most prominent muscle is the long thick TA muscle, on the lateral tibia surface, as shown in Figure 2.6. It targets the foot with Dorsiflexion and inversion actions. The movement is to raise the foot sole from the ground level and bend its inside upwards.

   TA originates from the upper tibial shaft along the interosseous membrane and terminates by inserting into the interior of the cuneiform at the first metatarsal bone. TA is the most superficial bone in this compartment and hence chosen for the study.

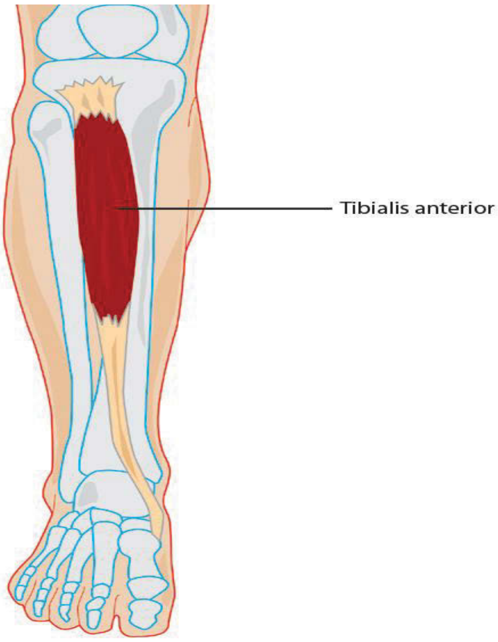


Figure 2.6 Tibialis Anterior Muscle (Levangie & Norkin 2011)

The Extensor muscles - Hallucis Longus (HL) & Digitorum Longus (DL) - are the deeply located muscles under the TA in the anterior compartment. They are laterally placed and take part in raising the foot soles to the front upon contraction (foot dorsiflexion). HL extends the big toe while DL extends the others.

They originate along the interosseous membrane from the fibula shaft and the tibia condyle inserting into the distal phalanx of the big toe and phalanges on the other toes respectively.

2. Posterior Calf muscles

All the superficial muscles in the calf insert into the Achilles tendon attached to the calcaneal ankle bone. These large and strong muscles maintain upright erect posture. This is the GA muscle. Plantaris is also a superficial muscle while TP & Soleus are deeply placed (Levangie & Norkin 2011).

Gastrocnemius (GA) is the largest and the most superficial and visible calf muscle. The prime role is to lower the foot sole to the ground and assisting in moving the lower leg back-region up and backward in the buttocks direction.

They thus target the foot through the plantar tibia or fibula flexion. The starting point is the femur condyles and endpoint the posterior calcaneus.

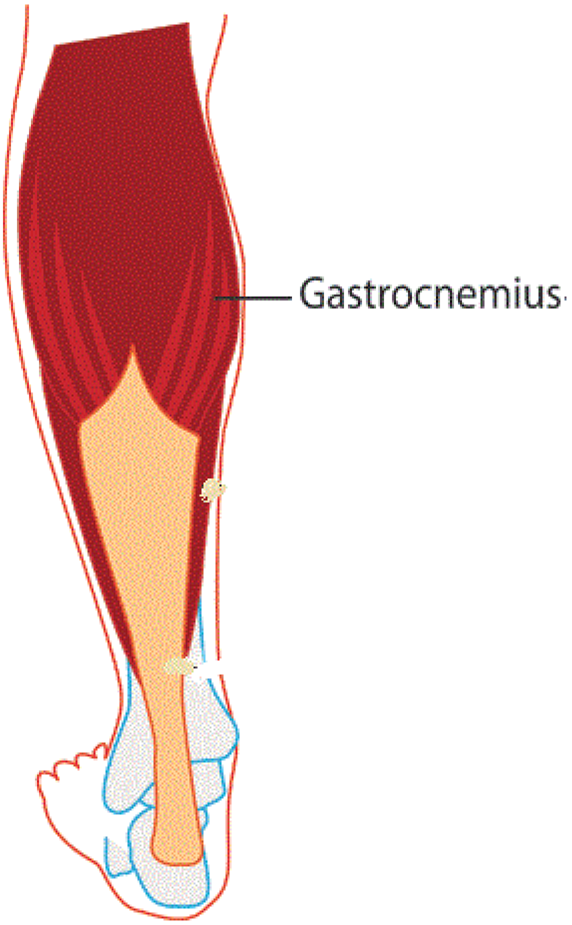


Figure 2.7 Gastrocnemius Muscles(Levangie & Norkin 2011)

Soleus, Plantaris & Tibialis Posterior (TP): Soleus is placed further deep from the GA, and is wide and flat. Plantaris occurs obliquely between the two sections. All three focuses on lowering the foot, plus Plantaris works on aiding the GA functions. Soleus has the extra role of maintaining posture during walking action.

Popliteus and the Flexor Muscles (Digitorum Longus or DL & Hallucis Longus or HL) are the deep muscles in the posterior compartment. Popliteus functions by moving the lower leg back-portion towards the buttock, assisting in leg rotation at the knee and thigh. Flexors help lower the foot sole to the ground, bend the foot inside region upwards as well as flex the big toe (HL) and the four normal toes (DL) (Levangie & Norkin 2011).

2.3.3 Location of Lower Limb Muscles under study

Quadriceps Muscles: These muscles are located towards the front side of the thigh. The RF muscle originates at the hip joint and ends near the knee joint. VM is placed at the inner side of the front thigh, and VL is located in the outer region of the front thigh. The VI muscle occurs under the RF muscle. These three muscles start from below the hip joint and end in the knee joint (Levangie & Norkin 2011).

Hamstring Muscles: These muscles are situated in the back of the thigh. BF is positioned in the outer area at the back thigh. SM is found towards the back thigh's inner portion and ST in-between SM and BF (Levangie & Norkin 2011).

Tibialis Anterior Muscle: Named in short as the TA muscle, it occurs at the surface of the tibia bone and passes on through the far inside end of the tibia. It attaches to the bones of the ankle and foot (Levangie & Norkin 2011).

Gastrocnemius (GA) Muscle: The GA muscle is situated on back side of the lower leg (Levangie & Norkin 2011**).**

2.3.4 Functions of Lower Limb Muscles under study

Quadriceps (RF, VM, and VL): Quadricep muscles perform the crucial function of extending or straightening the knee joint. These muscles thus coordinate to execute various movements in activities like jumping, walking, running, and sit-to-stand. VM, VL and RF muscles used to extend the knee. As the RF crosses the hip joint, it also flexes the hips. The quadriceps are responsible for stabilizing the knee joint as well (Levangie & Norkin 2011).

Hamstrings (ST): The primary functions of the hamstrings are to flex the knee and to extend the hip. Along with Quadriceps muscles, these muscles are used to perform different tasks such as walking, Running, jumping and sit-to-stand. They function in opposing directions of quadriceps. That is why the two groups together are referred to as antagonistic muscles (Levangie & Norkin 2011).

Tibialis Anterior (TA): The TA muscle function is to extend the foot at the ankle joint, to enable walking action; that is, to lift the foot up and clear the ground(Levangie & Norkin 2011).

Gastrocnemius (GA): This muscle helps to push the human body forward. They are also involved in performing walking, running, dancing, etc. This muscles also prevent human from falling (Levangie & Norkin 2011).

2.4 Context: Trend of High-Heeled Shoes & its Negative effects

In all cultures and societies globally, high-heeled shoes being part of etiquette trends and classy fashions is commonplace. Many illustrations show the inspiration of the latest street style of spiky footwear across the globe. Both latest fashion as well refreshing classic designs of heeled shoes are in use today. Iconic profiles and original designs of shoes are available for both gents and ladies.

2.4.1 History and Origin of Heeled Footwear

High-heeled footwear was part of traditional cultures for centuries throughout the post-classical history. The book “Shoes: An Illustrated History” by Rebecca Shawcross (Bloomsbury), describes in full essence the multitude of techniques to clad our human feet (Lindholm 2015).

The ancient Egyptians had them as a prominent accessory in their cultural outfits, as per documentation from around 4000 B.C. This practice is considered to be the predecessors of today´s high-heeled footwear (Paslawsky 2008). The oldest illustration of shoes was that of instruments that were similar to mocassin. They were dated from around 3500 BC and were discovered in Armenia.

Figure 2.8 Illustration on the evolution of styled footwear as of today: from top left to bottom right in the reading order - Chopines from 1400s, The first heels of 1590, Viva la difference from 1660, The red heel from 1670, Pompadour heel from 1750, Flat('The history of high heels — from Venice prostitutes to stilettos' 2015)

The first chronicled change in formal outfits, showing the addition of shoes as a necessity, was for Men. The European aristocracy of the 1600s started off this practice. During the medieval times, heeled sandals and shoes were the general accessory components of some sections of the society. These were the royalty, the elite, the wealthy and the invisible classes (included ladies like escorts and courtesans). Towards the onset of the middle ages, heeled foot accessories have become quite prominent, yet limited to a small fraction of the world population. Throughout all these times, the social code was for women never to bare their legs and feet, so the designs were pretty discreet('The history of high heels — from Venice prostitutes to stilettos' 2015).

The Victorian and Elizabethan eras showed a prominent rise in the widespread adoption heeled footwear. The 19th century brought high-heeled foot accessories to the continent of the US, and the subtlety continued – stockings and hosiery always accompanied them ('The history of high heels — from Venice prostitutes to stilettos' 2015).

The World War came with a drastic change in this industry when Christian Dior & Roger Vivier designed Stilettos. This permanently changed the market for designer footwear. The name was derived from an Italian word, which roughly translated to a ‘dagger with the tapering blade.' Pointed narrow toe base also characterized stilettos. Together with the needle-like heel, the designs were quite aesthetic, giving a streamlined appearance to the otherwise broad anterior feet region, which was visually appealing.

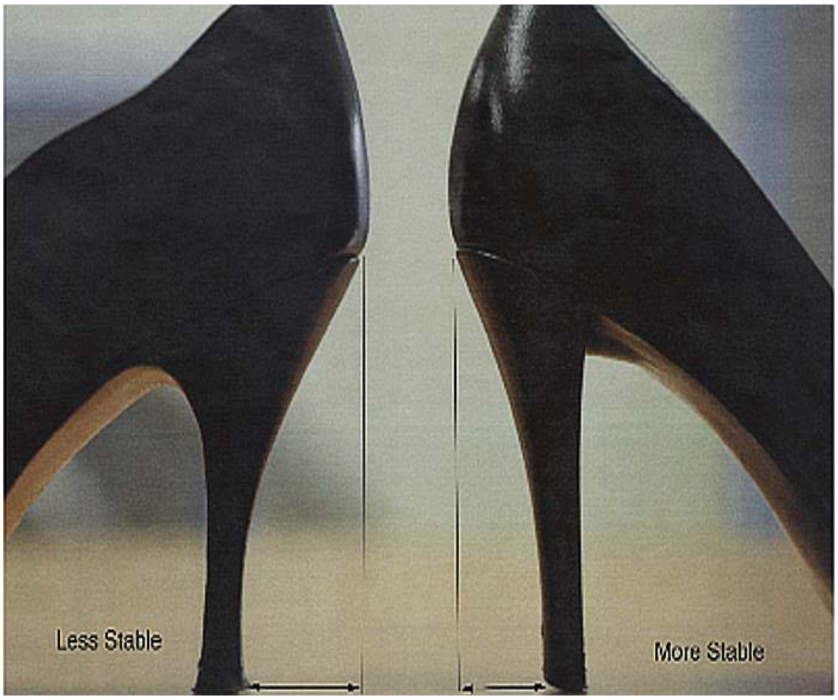


Figure 2.9 Stiletto heels and their stability demonstrated (Sanders & DPM 2011)

The Golden Age came with the rise of fame and stardom from of Hollywood. It gave birth to a more glamorous styling of women’s footwear, ditching all conventions and etiquette codes. The iconic stars and their trendsetting outfits instilled the transforming of footwear industry starting with the peaking demand for such glitzy leg outfits.

Trend-setting shoe and sandal designs were created by Salvatore Ferragamo, with the invention of the wedge heel in 1933. This added comfort and mobility to users of such heels.

1. The Early 1900s: Influence of the Victorian era, Woman's foot weren't visible in public, So long, heavy skirts were accompanied by laced-up pump, low-heeled shoe. By the '20s, hemlines and heel heights rose, with multiple straps across the top of the foot.

2. The '30s: or Golden Age of Hollywood - The wedge was invented along with shoe-sizing system , cork and glass heels, metal framework for the & structure.

3. The '40s: WWII brought many Women got into the American workforce, coupled with sensible chunkier high-heels and platforms, like high-throated pumps and oxfords.

4. The '60s: hemlines were pretty short, & chunkier, high-platform heels and go-go boots blended into Hippie culture in the late '60s' new androgynous fashion.

5. The '70s: Disco fever & glam rock & interchangeable platform wear, in psychedelic colors, metallic skins and patterns; as well as clunky combat boots & Creepers.

6. The '80s: Independent working women used high heel pump. in a wide variety of hues, materials and heights, like Cabochon jewels, patent leather and animal patterns.

7. The '90s: More elegant and streamlined, footwear of minimalist look, for designer runway shows, chic, refined elite dress code, the perfect high heel were the sexy yet sophisticated ones.

5. The Millenium: DIY trends emerged, allowing women to choose their own looks, Heels rose up to 7 or 8 inches; platform Spike, cone, block, wedge & invisible heels decorated with fur, studs, mirrors, jewels, fringe and even fruit.

Figure 2.10 Illustration on evolution of footwear trends in the 19th century (Alvarez 2013)

Another turning point was the launch of Platform shoes – a result of the gradual thickening and height drop of the shoe soles. Platforms are in a way attractive as well as less strain inducing, thanks to the right angle preserved at the ankle, and evolved quickly through the style markets.

Heels came back to the talk-of-the-town status in the 1990s, while corporate and professional cultures strived to maintain flats as standards. However, not long after, sophisticated designer heels became embedded in the professional world, coupled with the overall makeover of working-women outlooks. The increasing female employability, tapping of every professional phase by lady officers and rise in working classes indirectly contributed to this change, which continues till date (Alvarez 2013).

2.4.2 The Modern-Day Definition

In modern days, many women wear different types of high-heeled shoes (HHS) in professional, personal and social settings (Chien & Lu 2017; Hsue & Su 2009). What used to be a trend to attend parties, social and official events like fundraisers or celebrations, has now turned out to be an etiquette protocol.

The standard definition of high heels was often debated upon, by manufacturers, health advisors, and the wearers themselves. Heights of 2 to 3 inches were deemed the start of high-heel range by retail standards. Median High heels were between 4 and 5 inches. Beyond that were categorized as Extreme-high heels. However, nowadays, around 3 inches has become the commercial norm, and anything lesser was classified Flat or thick-soled. Hence greater than 3 inches of heel-heights were considered as the high-heel-height scale in research and industrial development (Picken 2016).

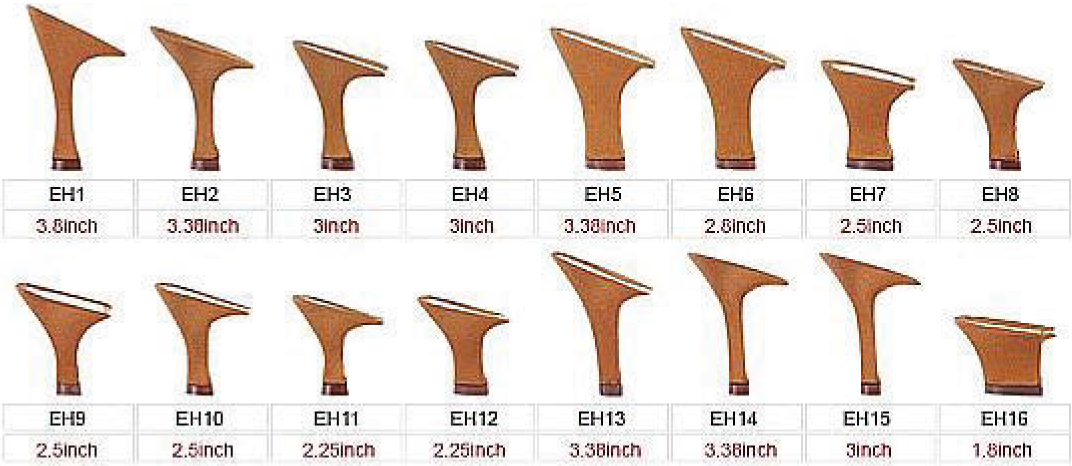


Figure 2.11 Retail standard heel-heights widely adopted (Picken 2016)

Daily use of High-heeled shoes is now part of professional culture anywhere in the world. Despite globally varying official outfit styles, heels are customized to sleek designs and chic fashion in men and women. According to previous research, 37% of women wear high-heeled shoes for their work and 39 % women wear HHS on a daily basis (Frey et al. 1993). The widespread adoption heeled footwear has been justified by varying angles of reasoning. Some of those common arguments are listed below:

- Heels make walking style appear more attractive in women, giving them a sassy appearance.
- It renders a greater level of feminine touch, as well as visual appeal.
- Heels are often part of official dress code, and they are culturally ingrained.

Many women have also come to believe that wearing such type of shoes helps them gain self-confidence (do Nascimento et al. 2014; Mika et al. 2012).

Figure 2.12 General use of High heels across various sections of the society (The curtesy the Friday Review, The Hindu published in New Delhi)

2.4.3 Adverse Effects of High-Heeled Shoes on the Human Physique

Research in the last few decades has uncovered that many women who are habituated to wearing high heels suffer from varying degrees of physical ailments. The main reason is deduced to be the wrong choice of heel heights and shoe models. The streamlined sole, while aesthetically pleasing, applies compressive pressure across the toes. This affects the body weight balance and gait through the distributed force on the foot sole on the ground, and in turn affecting all the forces that act along the spine and lower portion of the body. The biological rule for choice of heel heights is as shown in Figure 2.13, which is seldom followed.

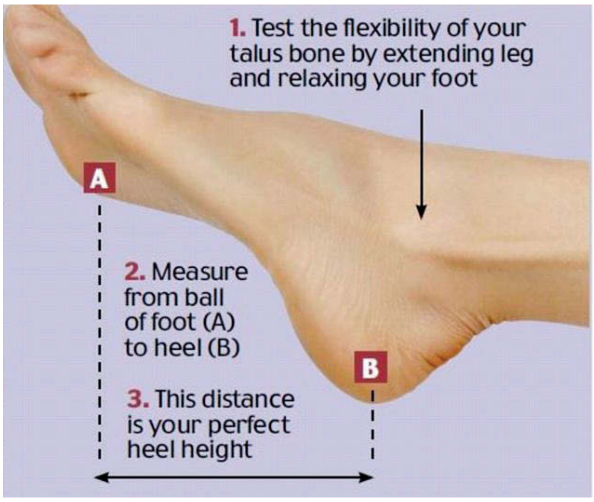


Figure 2.13 Standard rule for choice of appropriate heeled-footwear (Smellie 2016)

The commonest among them is mild to severe lower back pain (Bird, Bendrups & Payne 2003; Cronin 2014; Kim et al. 2011). Regularly wearing such shoes also lead to changing gait mechanics. Results also manifest as musculoskeletal problems including knee osteoarthritis, low back pain and muscle fatigue (Edwards et al. 2008; Nam et al. 2014). Moreover, HHS has been associated with an increased potential in women for frequent slips and falls (Cronin 2014; Williams & Haines 2014). All of these effects occur much amplified in women who are involved in physically active routines such as the professionals and student sections of the society.

Adverse impacts of wearing HHS on women's health have been recognized for an extended period (Foster et al. 2012; Linder & Saltzman 1998; Nam et al. 2014). One research (Williams & Haines 2014) showed that there is a positive relationship between the type of injury and usage of HHS. They scanned the Victorian Emergency Minimum Database and found that there have been 240 medical incidences caused by wearing HHS from 2006 to 2010. A recently published study investigated the epidemiology of HHS-caused injuries in the United States (Moore et al. 2015). During eleven years (2002 to 2012), the rate of occurrence of injuries directly as a result of HHS wearing has increased by 82% approximately. This study further stressed the danger and socio-economic cost of wearing HHS (Moore et al. 2015).

Figure 2.14 Principle pressure points while walking, with and without heels, and the consequent ache-experiencing regions('HOW HIGH HEELS AFFECT YOUR BODY')

The survey in (Shoes 2010) was conducted on 3000 women as test subjects who wear HHS regularly. It published that 10% of women had to undergo a medical examination or even be admitted to hospital because of wearing HHS shoes. Nearly 55% of women had their ankles twisted. This survey revealed that the most common type of injuries that happened because of wearing HHS were broken ankles, twisted knee, infected blisters, bunions and torn tendons (Shoes 2010).

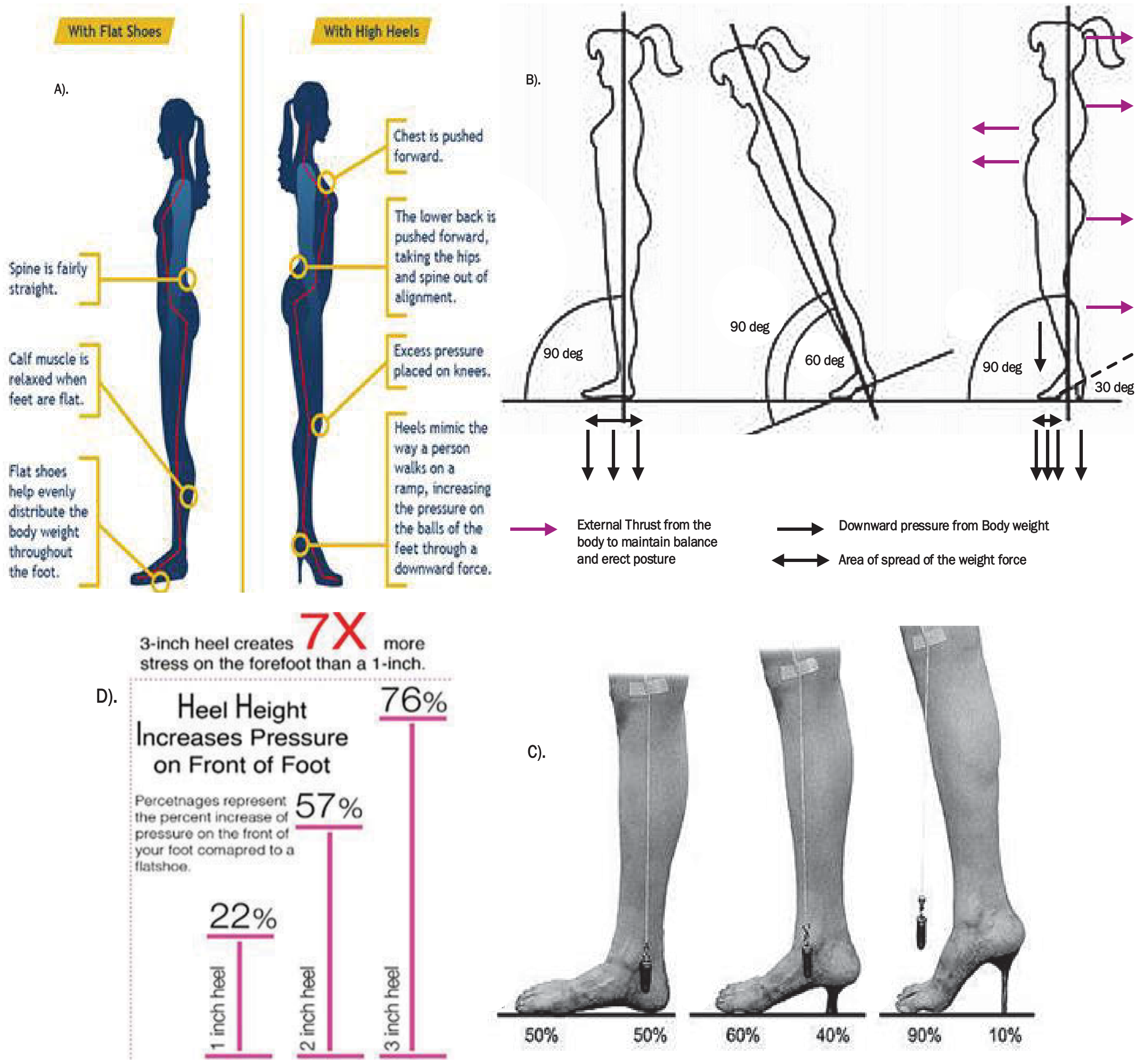


Figure 2.15 Effects of heel heights – A). Change in Posture mechanics , B). Change in Force vectors across the physique, C). Shift in Centre of gravity of the body, which can cause internal and external biomechanical changes, and D) Relationship between Heel Height and pressure on Front Foot ('HOW HIGH HEELS AFFECT YOUR BODY')

Daily use of high-heeled shoes changes biomechanics of the Body and increase the spinal curvature. Such habits cause Low Back Pain (United Nations) and leg pain due to the additional weight on toes (Hyun & Kim 1997; Lee, Jeong & Freivalds 2001; Yoe 1994). Other adversative side effects of wearing HHS was revealed in previous research such as shortened Achilles tendon (Scholl 1931), increased oxygen consumption (Ebbeling, Hamill & Crussemeyer 1994; Mathews & Wooten 1963) decreased stride length (Adrian & Karpovich 1966; de Lateur et al. 1991), walking speed and mobility (Alexander 2010; Murray 1970) and osteoarthritis in the knee (Kerrigan, Todd & Riley 1998).

2.5 Context: Electromyography and Signal Processing

2.5.1 Function & Significance of Electromyography

Electromyography (EMG) is a kind of bio-signal processing method to measure and analyze electrical activity incurred in the muscle contraction. A motor neuron, which is situated in the spinal cord, initiates the muscle activation. The neuron when fired will raise an action potential, which propagates from the neuron to the associated linked muscle fibers. This electrical signal, known as a motor unit action potential (MUAP), is the continuous-time data stream recorded as an EMG signal or graphing (Stephen 2013)

The data contained in EMG recordings is applied in determining the comparative surge and drop in muscle activity; it also translates to the on/off timing pattern of a muscle. However, they do not capture information on the nature of a muscle contraction event – as concentric, eccentric, voluntary or involuntary. Furthermore, the EMG signal can define neither how strong a muscle is nor if one muscle is stronger than another (Konrad 2005).

Instructions to Prepare for EMG Signal Recording: Placement & Use of surface electrodes

a) Preparation of Skin

1. Apply Alcohol on the skin surface for the removal of dirt, oil, and dead skin.

2. Excess hair is to be shaved if necessary, as it will impede signal flow. (Ideally this is a mandatory step accodding to SENIAM guidelines, but maybe non-feasible in many cases.)

3. For excessively dry skin, dabbing the area cleaned by alcohol with some electrode gel is necessary.

4. For extra sweat nature of the test subject's skin, spraying an antiperspirant on the cleaned patch of skin is important.

b) Electrodes Placement

1. There are specific rules and regulations for methods of surface-electrode placement. (Norris, Johnson, Perotto)

2. General sets of guidelines are also to be followed for large groups of muscles.

   a) The best possible locations are above the largest mass of muscle, with electrodes with aligned directly with the muscle fibers.

   b) Using motor point mapping procedures and motor point finders to identify the right position with reference to general location charts are also important.

c) Cross Talk Elimination

Cross Talk is not a real problem in cases including large groups of muscles. They may be circumvented by adjusting the size of electrodes, inter-electrode distance or using fine wires for measurement.

d) Precautions necessary

1. Skin placement should be perfect.

2. Avoid movement and relocation of electrodes by applying grip om straps or tape of the electrode to secure it firmly.

3. Avoid leads being bent, and they are to be placed pointing in the direction of the continuing wire strip (e.g., For extremity placed electrodes, the lead should point towards the proximal end of the extremity. This prevents the wire from bending towards that direction.)

4. Avoid stress on the wires; ensure them being loose underneath the tape or wrap holding them in position. Always check when the wires cross the joint and ascertain that the wires are not drawn taunt if the joint is fully extended.

5. Avoid placing electrodes over scars or aberrations.

e) Testing Procedure

1. Manual muscle tests are sufficient to assure proper signal reception and correct placement above the intended muscle.

2. Practice a trial session to check signal strength & quality and to familiarize the subject with the setup and instrumentation.

2.5.2 Signal Analysis of EMG Recordings

a) Time Domain Analysis of EMG

In the classic clinical sEMG analysis, the Surface Electromyography or sEMG signal was studied based on visual observation and inference of the amplitude, time duration and a number of phases. A few clinicians had the practice of listening to the sEMG signal through a loud speaker as a diagnosis measure. The visual or audio observations are limited to a simple signal inference. They were in turn heavily influenced by the technical expertise of the clinician. Of course, it demanded years of practice, and a vast variety of patient-subjects and physical symptoms, to comprehend the entire array of signal observations and inferences. Such knowledge technically spanned over very long periods of acquisition, and also limited the efficiency of the clinicians.

Thus, it is important to mathematically develop an accurate automated procedure of analysis for sEMG signals. A mathematically developed automated system also helps us understand and analyze more complex sEMG signals (Basmajian & De Luca 1985; Criswell 2010).

Most of the time domain features that have been used are related to the magnitude of the sEMG signal. Following are the most commonly used parameters.

i. Root Mean Square

Root-Mean-Square is a statistical measure of information content in a signal or data. Any information set containing non-positive values average out to zero (as in a sinusoidal signal). Hence mean estimates won't work for interpretation of such signals. RMS on the other hand, helps extracts the magnitudes alone, of the given input, irrespective of polarity. Thus, we get unbiased observations.

ii. Envelope of Rectified Signal

The envelope is another useful measure in decoding time-domain series. It is the record of the edges or extremities of a rapidly varying alternating signal. In such waveforms, the time-reflected variations are of less importance than the overall range of amplitudes, which is represented by the envelope of the waveform.

Envelop measurement based extracted information, related to the magnitude of the signal, results in the smoothing envelope of the rectified signal. It is done by suppressing the high-frequency fluctuation or harmonic components of the signal by using a Low-Pass filter. In the digital signal processing domain, the smoothing process is implemented by the Moving Window Averaging technique.

Moving Window or MA process of smoothing of signals is done based on partially-overlapping observation windows shifted along the time axis. The entire signal is chunked into segments of smaller duration with the header and trailer regions overlapping into the preceding and succeeding windows. The acquired signal subdivisions are processed on any specific feature or parameters. These values are then averaged to obtain the cumulative reading.

iii Zero Crossing

In Signal Theory, the zero-crossing point of a continuous time waveform is the time instant where when the signal amplitude crosses the reference line (the threshold). These points show the alternating nature of the signal, reflects on the frequency as well as the amplitude swings. The process hence determines the density of the zero-crossing within a specified period (e.g., one second), from the frequency-domain perspective.

b) Frequency Domain Analysis of sEMG

Frequency domain analysis of a signal is the extraction of relevant formation from the frequency perspective or reference frame of the signal. The data obtained from such techniques include frequency mappings, spectral components, harmonics, basis vectors and so forth. A whole variety of spectral transformation functions are used for time-frequency signal mapping, such as Fourier analysis, wavelet transforms, and discrete sine and cosine transforms.

Frequency analysis of sEMG signals is commonly performed by calculating the power spectral density of the signal with Fourier transform. The power spectral density indicates the strength of the signal at each frequency component. It translates to the density of the signal spectrum per frequency bin of observation. Power Spectral Density (PSD) has been widely used for fatigue analysis of sEMG signals. In a fatigued muscle, the shape of the frequency spectrum changes such that the median frequency shifts towards the lower frequency region of operation (Criswell 2010). The power density spectrum of sEMG signal indicates the average strength of the frequency component of the signal.

2.6 Literature review: EMG analysis on Lower Limb Muscles

Many significant works have been published linking the above-explained parameters, and functioning of lower limb muscles and activities to the various effects and behaviors manifesting in the human body. A few of the selected works, highlighting the need for our proposed methodology is examined and scrutinized below.

2.6.1 Studies Based on Individual Muscle Activity

(Kim et al. 2011) reported that high-heeled shoes alter the EMG amplitude of the upper leg and lumbar muscles during an STS task. Their findings suggest that elevated heel heights have the potential to induce muscle imbalance during STS tasks. In another study, (Goulart & Valls-Solé 1999) reported the postural and execution EMG activity of the leg and thigh muscles during STS task. They found out that the pattern of muscle activities remain constant when the initially seated posture changed. They also demonstrated that postural adjustments and balance-maintaining systems in the human body were well under control when the initially seated posture changed

The inference of these studies was to establish the need for a better perspective towards understanding high-heel shoes induced muscle activation pattern alterations during STS and other routine activities and functional tasks. STS tasks demand optimum neuromuscular coordination and postural changes to maintain steadiness of movement and prevent loss of balance (Kim et al. 2011;

Linder & Saltzman 1998). According to Dehail et al (Dehail et al. 2007), safeguarding human postural balance, our body has to make necessary adjustments in various systemic activities like neuro-muscular coordination and musculoskeletal dexterity. One such modification is during the walking & the STS tasks performed while wearing high-heeled shoes. Barton, Coyle & Tinley (Barton, Coyle & Tinley 2009) reported that regular usage of high-heeled shoes for STS and related tasks contributes to changes in body posture, and induce low back pain in women.

The human body is complex and has a flexible locomotion system that enables a normal human being to locomotor without falling, even in an unstable environment such as uneven surfaces, over ice, in the darkness and on high-heeled shoes (Alkjær et al. 2012). Previous research investigated that walking in high-heeled shoe affects biomechanics parameters of the body such as stride length, the width of footsteps, and foot progression angle. Maintaining balance and stability of the lower limbs and hence the body, require these factors to decrease with increasing heel height (Árnadóttir, Kjartansdóttir & Magnúsdóttir).One research has reported that walking with high-heeled shoes can be hazardous to balance and stability even on a planar surface (Barbieri 1983; Frey 1994; Menz & Lord 1999). Human biomechanics and muscle activities significantly alter while walking on HHS (Cronin, Barrett & Carty 2012; Esenyel et al. 2003; Kerrigan, Lelas & Karvosky 2001; Kerrigan, Todd & Riley 1998; Lee et al. 1990; Opila-Correia 1990a; Opila-Correia 1990b; Simonsen et al. 2012). Increased metabolic energy cost (Ebbeling, Hamill & Crussemeyer 1994) and Lower limb muscles activities have been associated with walking on High heels shoes (Esenyel et al. 2003; Joseph 1968; Kerrigan, Lelas & Karvosky 2001; Simonsen et al. 2012).

These studies suggest that walking on HHS demands specific strategy of neural control, which is different from walking on Flat shoes (Alkjær et al. 2012). Higher Entropy has been associated with high-heeled walking as compared to barefoot, that means movement variability increases with walking in HHS (Alkjær et al. 2012).

The RMS Signal analysis technique (from section 2.4.2) was adopted for a vast number of perspectives into the problem of adverse conditions induced by HHS. Few of the prominent findings are listed in Table 2.1.

Table 2.1 Research Articles that helped in interpretation of the RMS analysis

S.No.	Title of the paper	Research outcome
1	"An exploration of emergency department presentations related to high-heeled	The quadriceps muscles activation strength is higher, to prevent knee collapse.

	footwear in Victoria, Australia” (Williams & Haines 2014)	
2	“EMG and kinematics analysis of the trunk and lower extremity during the sit-to-stand task while wearing shoes with different heel heights in healthy young women” (Kim et al. 2011)	Quadriceps muscle activities were increased to compensate for the tendency to flex the knee during STS.
3	“Kinetics of high-heeled gait” (Esenyel et al. 2003)	Lower limb muscles activate more (stronger activations) to induce balance while walking on high-heeled dress shoes as compared to low heeled sports shoes
4	“Patterned Electromyography activity in the sit-to-stand movement” (Goulart & Valls-Solé 1999)	The pattern of muscle activities remained constant when the initial posture changes during STS.
5	“Kinematic and electromyography analysis of rising from a chair during a “Sit-to-Walk” task in elderly subjects: role of strength” (Dehail et al. 2007)	Postural balance maintenance in the human body requires necessary adjustments.
6	“Movement Behaviour of High-Heeled Walking: How Does the Nervous System Control the Ankle Joint during an Unstable Walking Condition?”(Alkjær et al. 2012)	walking on HHS demands specific strategy of neural control, which is different from walking on Flat shoes
7	“Footwear and postural stability in older people.” (Menz & Lord 1999)	Walking with high-heeled shoes can be hazardous to balance.
8	“Strategies of muscular support of varus and valgus isometric loads at the human knee” (Lloyd & Buchanan 2001)	To prevent falling while walking on high-heeled shoe Hamstring and Calf muscle increase their activation
9	“Agonist muscle activity and antagonist muscle co-activity levels during standardized isotonic and isokinetic knee extensions.” (Remaud, Cornu & Guével 2009)	To avoid imbalance, falling and instability while walking on unstable conditions lower limb muscles compensate their activities which stabilize the muscle activations pattern irrespective of the walking condition

10	“The pattern of activity of some muscles in women walking in high heels.” (Joseph 1968)	Increased metabolic energy cost and Lower limb muscles activities have been associated with walking on High heels shoes

2.6.2 Studies Based on Muscle-pair Synchronization: Co-Contraction

Apart from individual muscle activities, in favor of performing any task, multiple muscles coordinate with each other following different patterns and timings. Quadriceps and hamstring muscles are responsible for walking and STS task (Levangie & Norkin 2011). Walking and STS activities require higher muscle strength and coordination in balance systems than other daily activities (Abe et al. 2010). These tasks demand posture adjustments and an optimal neuromuscular coordination of the quadriceps and hamstring muscles (Bolink et al. 2012; Buckley et al. 2009). In regard to maintaining stability and balance around the knee joint, these muscles should function in opposite directions.

Co-contraction is a prominently studied parameter in muscular operation and mechanics. It is widely defined as the *“simultaneous activation of antagonistic muscles crossing a joint”* (Gardinier 2009). The most important interpretation of Co-contraction measurements is to reinforce ligament functioning by maintaining joint stability, improve resistance to rotation at the joint, and equalize pressure distribution at the articular surface (Baratta et al. 1988; Solomonow et al. 1988).

Co-contraction manifests as the synchronized activation of agonist and antagonist muscles (antagonistic pairs). It is visible in several daily events including a postural control for STS, walking, and running (Kellis & Kouvelioti 2009; Wang & Gutierrez-Farewik 2014; Weir et al. 1998). (Busse, Wiles & Van Deursen 2005) States that co-contraction is the mechanism that regulates the simultaneous activity of agonist and antagonist muscles crossing the same joint. Research shows that excessive co-contraction in muscles can cause inefficient or abnormal movements in some neuromuscular pathologies. It has even been associated with normal aging (Kellis, Arabatzi & Papadopoulos 2003; Palmieri-Smith et al. 2009). Due to increased mechanical demands associated with STS and Walking tasks, it is rationally inferred that activation of muscles located towards the lower extremity increases with the rising speed of gait (Janssen, Bussmann & Stam 2002; Lord et al. 2002; Roy et al. 2007).

Two important findings which can be significant in interpreting physiological mechanics concerning HHS usage were contributed by Palmieri-Smith et al. & Lloyd et al. The former shows that women appear to preferentially activate the lateral quadriceps and hamstrings muscles while simultaneously displaying less medial thigh muscle activation (Palmieri-Smith et al. 2009). Moreover, as quoted by Lloyd et al, "*the quadriceps and hamstrings muscles have the potential to provide dynamic knee stability because of their abduction and adduction moments*" (Heiden, Lloyd & Ackland 2009; Lloyd & Buchanan 2001).

An overwhelming effect of the Co-contraction metric is the increase in the net compressive contact force at the articular surface. Antagonist muscles are crossing a joint, under activation, has been shown to enhance joint compressive forces (Hodge et al. 1986). They have also been associated with progression of osteoarthritis condition (Hodge et al. 1986; Lewek et al. 2005). A lot more investigations were completed into co-contraction strategies, giving a detailed picture into the variant strategies. They explain the role of this adaptive neuromuscular strategy in the onset and progression of osteoarthritis regarding the ACL-injured population.

Multiple studies have shown older adults to have higher levels of muscle co-contraction than their younger counterparts during balance challenges (Benjuya, Melzer & Kaplanski 2004; Chu et al. 2009; Hortobagyi et al. 2009). Elevated muscle co-contraction has also been associated with a history of falling (Ho & Bendrups 2002). Enhanced co-contraction results in the stiffening of the joint. Here, increased joint stiffness is considered to be a compensatory strategy when faced with challenges in balancing (Allum et al. 2002; Cenciarini et al. 2009; Reynolds 2010). One research article exposed that co-contraction about the ankle increased when subjects were instructed to minimize their postural sway, especially with increased difficulty of static balance challenges (Reynolds 2010). Increased co-contraction, however, was not predictive of the amount of postural sway. The authors concluded that subjects might have employed a co-contraction strategy in an attempt to minimize postural sway which was not always successful. While increased ankle stiffness has been documented in older adults and adults prone to falls (Ho & Bendrups 2002), stiffening alone may not be a particularly effective balance strategy (Cenciarini et al. 2009). According to one research approach, higher co-contraction was found about the ankle during static balance challenges in an elderly group (Benjuya, Melzer & Kaplanski 2004), with a commensurate decrease in postural sway compared to a younger group.

Listing of more articles that compiled the inferences for Co-contraction analysis in this research are given in Table 2.2

Table 2.2 Research Articles that helped in interpretation of the Co-contraction analysis

S.No.	Title of the paper	Result and Conclusion
1	"Greater muscle co-contraction results in increased tibiofemoral compressive forces in females who have undergone anterior	The ACLR (Anterior cruciate ligament reconstruction) group demonstrated

	cruciate ligament reconstruction"(Tsai et al. 2012).	significantly greater muscle co-contraction as well as less knee flexion than the control group.
2.	"Compensatory strategies during walking in response to excessive muscle co-contraction at the ankle joint"(Wang & Gutierrez-Farewik 2014).	Higher value of co-contraction causes inefficient or abnormal movement in several neuromuscular pathologies. If co-contraction increases, the synergistic ankle muscles can compensate with opposing muscle pair co-contraction
3.	"Differences in lower-extremity muscular activation during walking between healthy older and young adults"(Schmitz et al. 2009).	The older adults exhibited higher value of co-contraction as compared to the young adults in lower limb muscles during walking
4.	"Increased fall risk is associated with elevated co-contraction about the ankle during static balance challenges in older adults"(Nelson-Wong et al. 2012).	Participants who were in the at-risk to fall category had significantly higher ankle co-contraction during all of the static balance conditions compared with participants in the not-at-risk to fall category
5	"Interaction between age and gait velocity in the amplitude and timing of antagonist muscle co-activation"(Hortobagyi et al. 2009).	Co-contraction was higher in older adults as compared to younger adults during walking
6.	"Ankle reflex stiffness during unperceived Perturbation of standing in elderly subjects"(Ho & Bendrups 2002).	Elevated co-contraction was associated with muscle stiffness
7.	"Aging-induced shifts from a reliance on sensory input to muscle co-contraction during balanced standing"(Benjuya, Melzer & Kaplanski 2004)	Higher co-contraction is needed during static balance challenges

2.6.3 Studies Based on Muscle pair Synchronization: Coherence

In a neural system, synchronization of motor neurons is considered essential for any muscle activity. Different neural oscillations in human beings have been a topic of research for several years. The key function of neural oscillations, regarding muscle activity, is to allow muscle synchronization while executing day-to-day tasks (Hansen et al. 2001). Quadriceps and hamstring muscle synchronization play a major role in human-executed walking and STS tasks (Levangie & Norkin 2011). During this synchronization, common neural inputs to these muscles come from the Central Nervous System (CNS). The most frequently occurring neural oscillations from CNS are observed in the Beta Band (15-30 Hz) (McManus et al. 2016) during regular activities such as walking and STS.

The frequency of Neural oscillations regarding common neural inputs is also referred to as the Common Drive. According to previous research (Gibbs, Harrison & Stephens 1995; Hansen et al. 2001), the common drive is present only in a synergistic muscle pair that has similar goals to enhance stability around a common joint during walking (synergistic muscles refers to those who engage in similar operations for a particular task). Common neural inputs to muscle pairs can be examined using EMG-EMG Coherence analysis during any day to day task (Halliday et al. 2003; Hansen et al. 2001; Petersen et al. 2010). Coherence refers to the synchronization pattern of muscle pairs in the frequency domain. It infers on how much a set of muscles correlate or engage in harmony.

Common oscillatory drive to a muscle pair is quantified by EMG-EMG coherence (Wang et al. 2015), which can be calculated using Welch's periodogram method (Wang et al. 2015).

Coherence measure assigns a unit-less real number between 0 to 1; larger values (closer to 1) corresponds to two signals perfectly coherent or synchronized in the frequency domain, while smaller values (closer to 0) indicate that the two EMG signals are not consistent or in synch. EMG-EMG coherence analysis is the most popular approach to assess the Common Drive. The fact is so because it is easy to obtain, requiring only the recorded EMG signals from muscles without the need to perturb or stimulate the system (Barthelemy et al. 2010; Bo Nielsen 2002; Hansen et al. 2005; Norton 2008). Previous studies indicated that muscle fatigue increases Beta Band coherence (McManus et al. 2016) which is related to greater muscle synchronization. Beta Band coherence can be expected to increase between motor units receiving common input that could be muscle pairs around the common joint and perform similar actions (Boonstra et al. 2008).

For studies that involve EMG recordings purely, coherence analysis can be used to understand the given coordination between a pair of muscles by looking at EMG signals in the frequency domain and identifying commonalities in strength and periodicity of at relevant frequencies. Additionally, through analyzing the strength and frequency band distribution of the coherence spectrum, the common neural inputs to motor neuron pools can be revealed. They primarily originate from the corticospinal pathway (Danna-Dos Santos et al. 2010). Some studies have also suggested that coherent oscillations in the motor system may direct activation of multiple muscles through respective mutual input from neuronal groups, creating a mechanism of efficient and effective interaction (Schoffelen, Oostenveld & Fries 2005).

Table 2.3 summarizes the significant findings in the light of Coherence analysis and its significance in Muscle synchronization studies.

Table 2.3 Research Articles that helped in interpretation of the Coherence analysis

S. No.	Title of the paper	Research outcome
1	"Muscle fatigue increases beta-band coherence between the firing times of simultaneously active motor units in the first dorsal interosseous muscle" (McManus et al. 2016).	Motor unit coupling occurred in the Beta band. Coherence was higher in fatigue conditions.
2.	"Synchronization of Lower Limb Motor Unit Activity During Walking in Human Subjects" (Hansen et al. 2001).	The Common drive is present only in a muscle pair that has similar goals to make stability around a common joint during walking.
3.	"Fatigue-related changes in motor-unit synchronization of quadriceps muscles within and across legs" (Boonstra et al. 2008).	Beta Band coherence can be expected to increase between motor units receiving common input that could be muscle pairs around the common joint and perform similar actions
4.	"Fatigue-related Electromyography coherence and phase synchronization analysis between antagonistic elbow muscles" (Wang et al. 2015).	Coherence was found higher in severe fatigue condition compared to minimal fatigue condition
5	"Central common drive to antagonistic ankle muscles about short-term Co-contraction training in non-dancers and professional ballet dancers" (Geertsen et al. 2013)	Improvement of the ability to maintain a stable co-contraction in the region of the ankle joint results from short-term plastic changes in the neural drive that is fed to the involved muscles (which will lead to newer learning of features). These changes are not necessary to maintain a higher performance level.
6	Motor Unit Synchronization and Neuromuscular significance (Semmler 2002)	Motor unit synchronization exhibits acute and chronic plasticity. The fact accomplishes that such synchronization trends exhibit deliberate strategies for neuromuscular activation. Motor unit synchronization has the most crucial function of

		increasing the rate of force developed while rapid contractions occur, They also function as a mechanism for coordinating multiple muscle activity under synergistic conditions.
7	"Respiratory Muscle Plasticity. Comprehensive" (Gransee, Mantilla & Sieck 2012)	The lower limb muscles make short-term plastic changes in the neural drive in unstable condition.

2.7 Problem Domain & Research Gap

Various studies have been done on HHS, such as the effect of HHS on Biomechanics, kinematics of body, gait pattern, knee joint, etc. previous studies also relate wearing HHS to low back pain, knee pain, ankle twisting, osteoarthritis. Etc.

2.7.1 Problem Domain: EMG Analysis of the Impact of HHS on Lower Limb Muscles

To maintain body-balance while moving around in HHS shoes, the human body adapts the lower-limb muscle system through some necessary changes and adjustments. These changes are maybe internal – like changes in muscle fiber length, muscle structure, etc., or external - such as stride length, step size, and neuromuscular coordination.

In muscular mechanics, the external stimulus (for instance, the wearing of HHS investigated in this research) necessitating adaptations in the limb muscles do not affect defining or quantifying such adaptations. There are two approaches to be considered for that purpose. The first approach is to identify or measure on an individual muscle basis. Some studies have explored individual or paired muscle analysis, in select few activities like walking and running.

The second approach is to consider some or all muscles involved in a particular balance compensating or maintaining the strategy. Lower limb muscles change their activation and muscle pair synchronization in coordination. This is true for both the tasks in consideration while wearing HHS. Muscular adaptation patterns for balance maintenance have been studied neither for this kind of movement nor for these muscle combinations.

Such a method can be considered superior because they give us information of the entire muscle system as one function. This is better than analyzing and correlating individual muscle readings. There are very few studies conducted on changes in lower-limb muscle activation patterns during walking and STS tasks while wearing HHS. The coordinated efforts have not been analyzed and appropriately documented yet. Hence, reflecting on pattern trends in HHS using test subjects allow us to understand how balance is maintained by the combination of muscles chosen in the proposed methodology.

2.7.2 Research Gap

The purpose of this research methodology is to inspect the patterns of muscle adaptation during balance maintenance and derive a methodology to study such behavioral changes.

Thus, the gap in existing research may be summarized in the following points:

1. Recent studies have mainly focused on the effects of HHS on Biomechanic, kinematic and kinetic changes during stair ascent/descent tasks. However, only a few studies have been done regarding the effects of wearing HHS on postural related muscle activities and postural changes during the Walking and STS task.
2. To our knowledge, effects of muscle co-contraction of HHS for STS and walking have not been examined yet.
3. Walking and STS task on High heeled shoes demands lower limb muscle synchronization changes or common neural oscillation changes to maintain stability around the knee, which has not been well documented yet.

2.8 Summary

The various parameters investigated for EMG analysis, the different features and functions of the motor muscle units, all play a significant role in maintaining body posture, lower limb stability, and health condition as well as long-term performance while executing our routine activities like walking & STS. The adverse conditions created due to the imbalance, the abnormal interactions, and out-of-norm external features have also been highlighted. In this context, the following are the highlight facts that are reference indicators for the rest of our investigation:

- There are various direct, indirect, long-term, and short-term negative side-effects of wearing high heel shoes on women body.
- Lower limb muscles engage in necessary changes in their activation patterns to establish postural balance and stability. Their activation is stronger while performing movements such as Sit-to-Stand and Walking, in relatively unstable conditions like on uneven surfaces, under poor lighting conditions, and with HHS.

- Stability in posture contributed from lower limb muscles increases with their co-contraction level. Higher co-contraction measures are directly related to muscle stiffness and muscular fatigue.
- Certain short-term plastic changes occurring in the human nervous system helps us avoid from falling and institute balance. Common neural oscillation takes place in the Beta band (15-30Hz) in the human body.
- Increased beta band oscillation was observed in unstable and fatigued conditions. The increased common neural oscillation has also been associated with a higher coherence value.

Chapter 3 : Theory and Methods

3.1 Outline of the chapter

Aim of this chapter is to present the experimental design used for validating the proposed hypothesis - to collect the raw EMG data form the experiments.

First, the demographic characteristics of the participants and their inclusion-exclusion criteria for the experiments are mentioned. After that, study procedure design and EMG data collection method from different lower limb muscles are explained.

Next, the procedure for STS task and walking task are explained to conduct the experiment. After that, export of EMG data and EMG data processing are explained.

At last, EMG data analysis is introduced which has been used in this research.

3.1.1 Mind Map

Below shown is the Mind Map of this chapter.

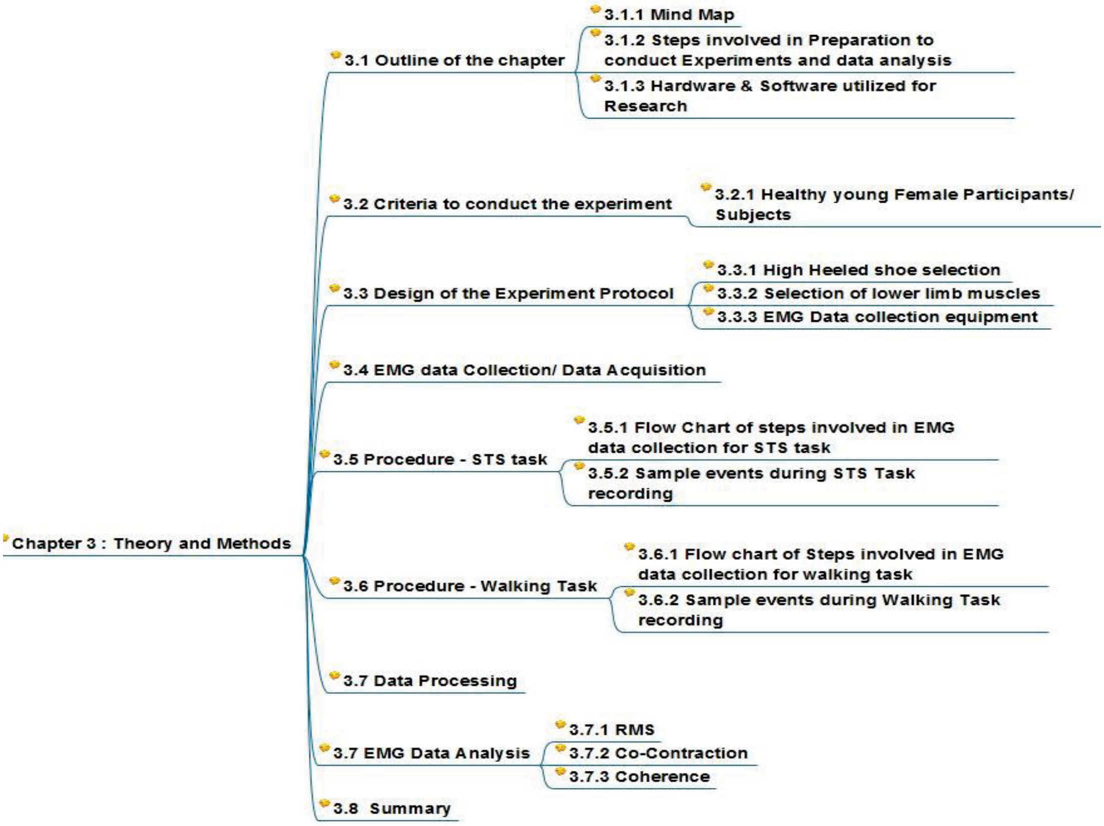
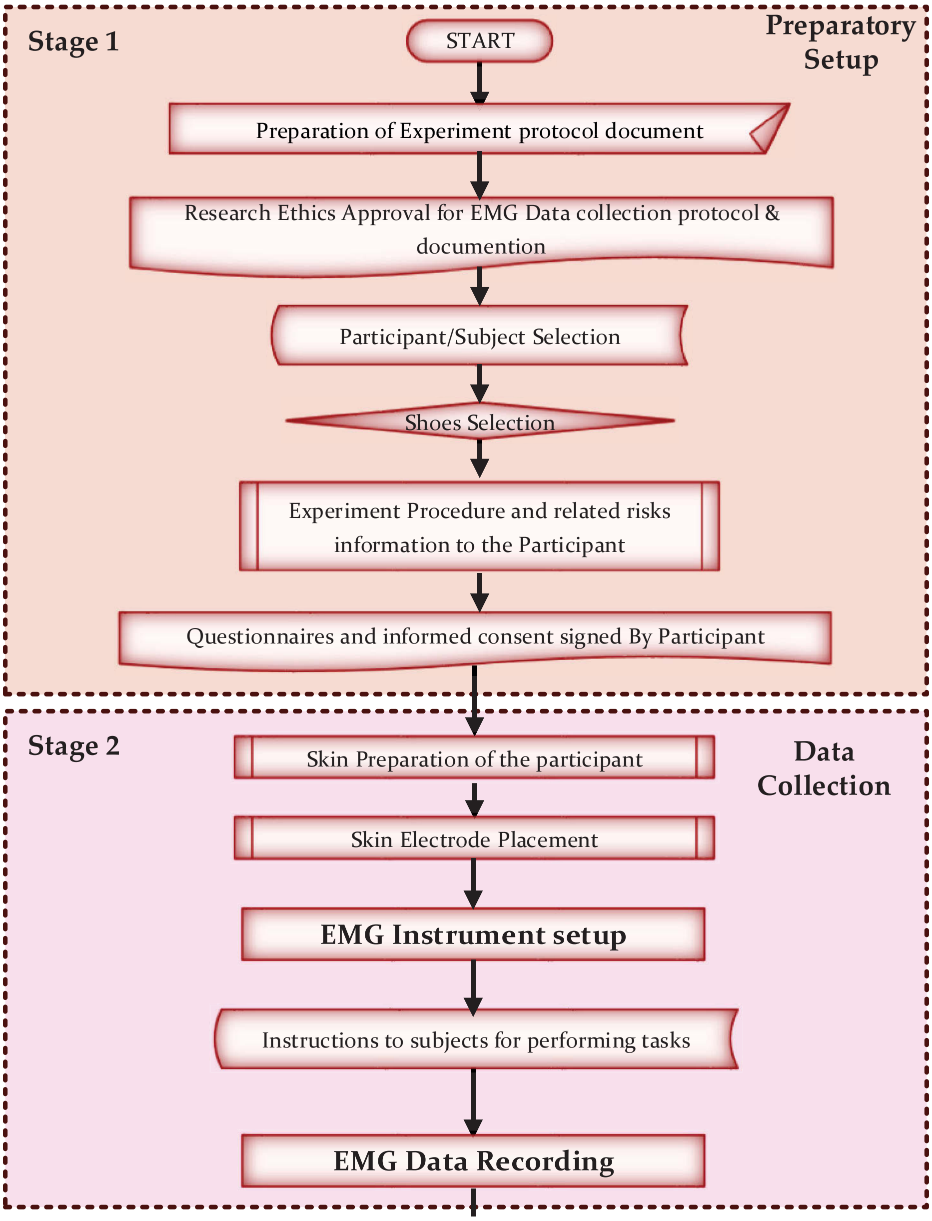


Figure 3.1 Experiment Design and Data Analysis Mind map

3.1.2 Steps involved in Preparation to conduct Experiments and data analysis

For this Research on walking and STS task with HHS, different steps were involved in EMG data collection experiment and Data Analysis.

First, an experimental protocol was prepared to collect EMG Data. The University Human Research Ethics Committee had approved the experimental protocol for this study. Female volunteer participants were selected based on well-defined inclusion and exclusion criteria as mentioned in the following sections. All procedures and risks were explained to the participants and informed written consents were obtained. The applicable risk measures, possible hazards in the lab environment and effects of the performing of the tests were explained, and the volunteers were required to declare their agreements.



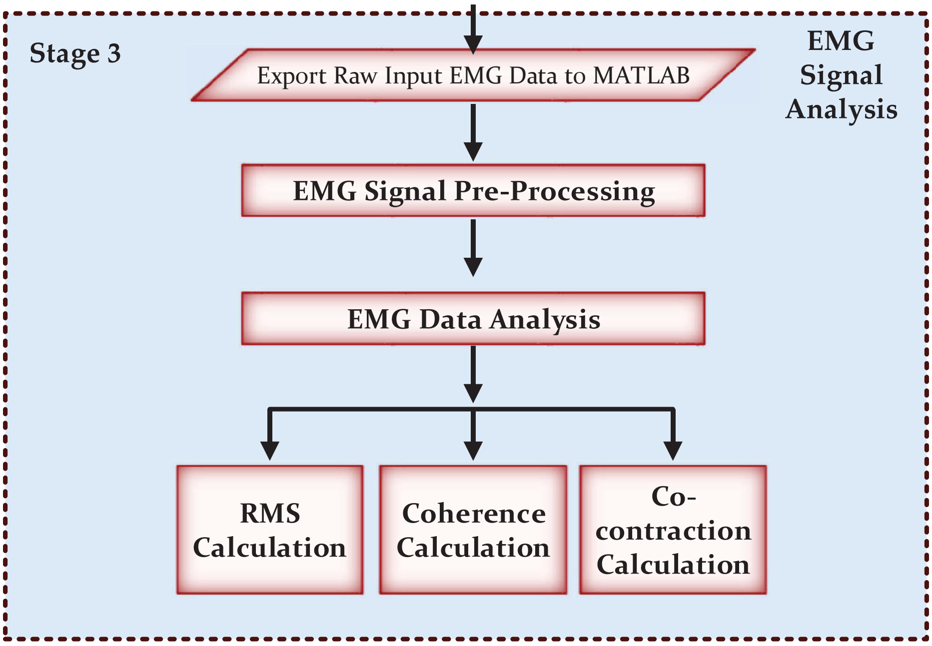


Figure 3.2 Experimental Design Flowchart

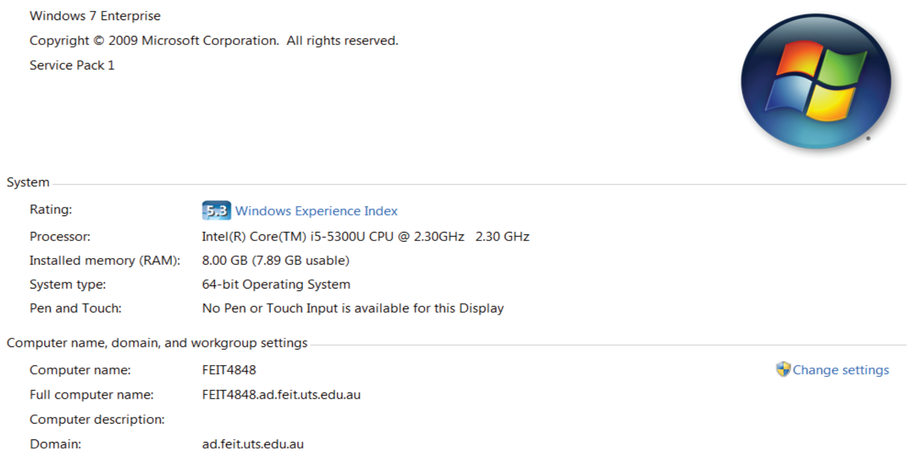
Participants had to give a completed Questionnaire as well before being taken into the experiment. This questionnaire had the main purpose of identifying valid information about determining foot dominance, as the participant's dominant leg was to be used for testing purposes.

Stiletto shoes with different heel heights were chosen for the experiment. Electrodes were placed on lower limb muscles, after skin preparations of participants according to the SENIAM guidelines (Hermens et al. 1999). EMG instruments set-up was done in the Centre for Health Technologies lab at UTS, School of Biomedical Engineering, for data recording. Test participants were given clear instructions on the performing of the task and were allowed to act continuously throughout each task duration. EMG Data Recording was started in parallel with the participant's activity, and exported raw EMG data was collected into the PC used for research. Then Raw EMG data was pre-processed in MATLAB software. EMG data were analyzed using RMS, Co-Contraction and coherence parameters. All steps followed in this experimental design is summarized in a flowchart shown in Figure 3.2.

3.1.3 Hardware & Software utilized for Research

The overall literature, analysis, and investigations were performed on a university provided research terminal, with basic specifications as given below in Figure 3.3

MATLAB R2015b was the software in use throughout the two-year research period, from the pre-processing to the final analysis. Toolboxes were not used much, as most of the required functions and mathematical operations were in-situ coded within the experiment setting. Basic built-in functions like the processing, image plotting, graph coding, etc. were also taken from the MATLAB generic library. Biograph infinity software was used for EMG data collection



Windows 7 Enterprise
Copyright © 2009 Microsoft Corporation. All rights reserved.
Service Pack 1

System
Rating: 5.3 Windows Experience Index
Processor: Intel(R) Core(TM) i5-5300U CPU @ 2.30GHz 2.30 GHz
Installed memory (RAM): 8.00 GB (7.89 GB usable)
System type: 64-bit Operating System
Pen and Touch: No Pen or Touch Input is available for this Display

Computer name, domain, and workgroup settings
Computer name: FEIT4848
Full computer name: FEIT4848.ad.feit.uts.edu.au
Computer description:
Domain: ad.feit.uts.edu.au

Figure 3.3 Hardware specifications of the system in use

3.2 Criteria to conduct the experiment

3.2.1 Healthy young Female Participants/ Subjects

Healthy young female participants having demographic characteristics as mentioned in Table 3.1 volunteered in this study. Participation of the females was done based on inclusion and exclusion criteria.

Table 3.1 Demographic characteristics of the participants used in this study

Variables	**STS task** **Mean ± SD**	**Walking Task** **Mean ± SD**
Total Number of Subjects	*10 Young Females*	*15 Young Females*
Age (Year)	*23.8 ± 1.8*	*24.2 ± 1.5*
Weight(Kg)	*51.2 ± 4.6*	*54 ± 3.9*
Height(cm)	*162 ± 4.3*	*169 ± 4.1*
Body Mass Index(Kg/m^2)	*18.6 ± 1.4*	*18.9 ± 1*

Inclusion Criteria:

All subjects were familiar with the usage high-heeled shoes and the possible health effects. However, the subjects were chosen such that they were not regular or frequent heel shoe users. It was mandated that they did not wear HHS daily.

The reason is that the hypothesis of this research investigates the effects of HHS on the lower limb muscle physiology in terms of short-time periods. Which means the plasticity effects had to be temporary and new, that the muscles were not used to such high-stress environment or triggers. This will allow the muscle to depict short-term adaptations, which is the focus of our study.

On the contrary, a regular or even a frequent user will have toned quads and calf muscles. This means that the activation patterns, neuronal firing and hence the common drive mathematical values will have already been modified and tamed to match the external impetus. That means, as suggested in the hypothesis, the measured values, or the physical signal strengths will be much different (possibly higher) than the regular heel-ankle-calf-thigh muscle operational measures.

Exclusion criteria:

To avoid improper recording of the signal, like falsely amplified or suppressed, toned or rectified (which corresponds to already achieved muscle adaptation to such stressful activity of the limbs regularly), the following criterion was used for the exclusion of volunteer participation.

- A history of lower back pain
- History of surgery based on the abdomen or back-region
- Spinal fractures
- Numerous another principle musculoskeletal health disorders
- Neurological and neuronal conditions
- Any Lower-body psychological problem
- Pregnancy
- Ankle pain
- Joint dislocation at the hips and knees
- Any sign or history of nacrossis
- Any deformities in the lower limbs
- Women under Menstrual Cycle

3.3 Design of the Experiment Protocol

3.3.1 High Heeled shoe selection

For this study, HHS with four different heel heights were chosen - 4cm, 6cm, 8cm, and 10cm which are considered as EH16a, EH11, EH15 and EH1 retail standards (Picken 2016). The shoes used for the experiments during two distinct tasks STS and Walking are shown in Figure 3.4, and the surface of the heels is approximately $1cm^2$ for all shoes, which is defined as a stiletto in the fashion industry. To maintain uniqueness, the shape and style of these shoes are chosen to be as much similar as possible. Care was taken that the Stiletto Heel stability criteria was maintained, as depicted in Figure 2.9.

Figure 3.4 Different heel height shoes used in experiment for (a) STS Task (b) Walking Task

3.3.2 Selection of lower limb muscles

The Lower limb muscle selection depends mainly on the location and role in the walking and sit-to-stand bodily functions. Chapter 2 section 3 (2.3) elaborates entirely the lower limb anatomy and physiology.

Two prime facts were taken into consideration from this study of the leg-muscle domain:

1. Superficial location of the muscles – This means that the muscle activation signals originating is be rather prominent and the recorded patterns in the EMG data bears strong correlations with high co-occurrence indices and comparable magnitudes. The deeply located muscles if studied presents with the risk of poor signal strength and suppressed pattern harmonics. Likewise, if they are coupled with superficial muscles investigation there will be a wide mismatch in the magnitude ranges and activation strengths numerically.
2. Muscle Functioning directly and solely contributing to movements of locomotion – The overall anatomy of the musculo-skeleton structure of the lower limbs in section 2.3 shows that there are multiple functions achieved for the human body by them. This includes movements like walking, changing position from sit, lean, stand, bend and turn to another, erect posture, etc.However, for our study, the focus was the activities which were most prominently undertaken under HHS usage, which is Walking and STS. Hence a careful inspection of the anatomy and system led us to pick those muscles directly contributing the limb and joint movements involved in these motions, and the corresponding micro motions like erecting the bone structure, maintaining center of gravity, bringing the foot and leg back to equilibrium, etc.

Concluding the short examination described in the listed points above, we inferred on the following muscle components for experimenting on:

- Rectus Femoris (RF)
- Vastus Lateralis (VL)
- Vastus Medialis (VM)
- Semitendinosus(ST)
- Tibialis Anterior(TA)
- Gastrocnemius Medialis (GA)

3.3.3 Physical Lab Settings for Experiment conduction

1. Space availability for Walking Task of 1-minute duration

The lab environment where the sEMG recordings were conducted was a rectangular room of 3 meters 5 meters. A free space of roughly 1.5 meters by 1.5 meters was available in the room. This space was available for the subjects to walk on HHS.

2. Armless and backless chair with adjustable seat for STS task

The chair was used for STS experiment is given in figure 3.5. Because different Participants have with various height, the chair in use was chosen as an extendible one. This was useful to maintain right angle (90 degrees) around the knee of the participants while sitting, by using adjustable seat height. The chair used in this experiment is shown in Figure 3.5.

Figure 3.5 Chair used for experiment during STS Task

3.3.3 EMG Data collection equipment

The EMG signal collection setup was part of the Centre for Health Technologies installations. The equipment setup was the product assortment from Thought Technology Ltd, one of the forefront biofeedback, neurofeedback and psychophysiological instrument manufacturers. The component devices and their specifications are detailed out below:

1. EMG sensors

Six EMG sensors were used for the six muscles under study. They were used to sense muscle activity while the performing tasks in consideration. The Myoscan Pro coded 02494 is given in

Figure 3.6 EMG Signal Sensor from the experimental setup

Figure 3.6. It is pre-amplified and used with the sEMG monitor channels A to F. They are compatible with the triode electrodes.

2. sEMG electrodes

The electrodes were silver-silver triode with a fixed inter-electrode distance of 2 cm and a diameter of 1cm (Manufacturer: Thought Technology, Montreal, Quebec, Canada).

Specifications: The sensor has Triode electrode structure. It has three leads located at a standard spacing of 2 centimeters. All three are Silver-Silver Chloride electrodes. The electrodes are protected against corrosion while they attach to the pre-amplifiers through a backing provided by Brass snaps that are nickel-plated. They are for single time use-and-throw only.

Figure 3.7 The three-leaded chloride electrode

3. Sensor Replacement Cable

The Replacement cable is necessary to make round-pin connections to the round protected pin encoders. Each cable is 60 inches long. The product from TTL is the Switch Sensor Cable, coded

SA9387M. It has been specifically designed for interfacing with the ProComp2 encoder.

Figure 3.8 Sensor replacement cable

4. Multichannel sEMG signal encoder

The Multi-channel sEMG signal encoder as shown in Figure 3.9(a) applied in our experimentation is the FlexComp System with BioGraph Infiniti Software, product code T7555M. It is a physiological monitoring and data acquisition for power users. It works based on a ten high-speed channels sampling at 2048 samples per second. The resolution is 14 bits, 1 part in 16364. It interfaces with the system sensors. The internal user-activated device calibration ensures the signal harvest is of the highest quality. Thus, the time lags and effects of re-calibration is eliminated.

(a) (b)

Figure 3.9 (a). Multichannel EMG Signal Encoder & (b). Compact Flash Signal transmitter

5. Compact Flash recorder

The Model used here is SA9600, Tele Infiniti Compact Flash as shown in Figure 3.9 (b). It enables the setup to operate on long-range real-time data monitoring, for the walking task. The antenna transmits data up to 100 meters. Transmission capacity is 2048 samples/second for up to ten channels, making it perfect for un-tethered situations, in remote data storage modes.

6. Electronic Gel or paste

For ideal skin preparation to increase the conductivity, a conducting gel is to be applied on the patch of the skin where the electrode will be attached. The gel that was used in the lab as part of our experiment preparation stages is shown in Figure 3.10.

Figure 3.10 Electronic Gel Paste in use

7. Biograph Infinity software platform

To record and display EMG signal provides flexible, high-speed processing of high-resolution data and allows clinicians to choose from a full range of user-defined screen configurations for specific

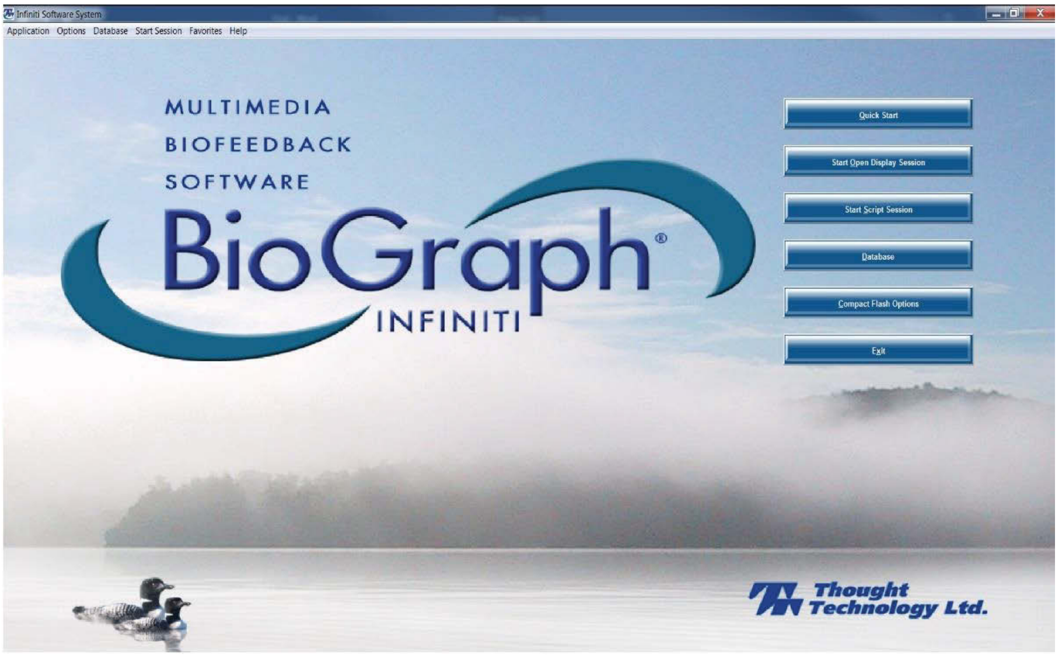


Figure 3.11 Biograph Infiniti Software used for the EMG setup

applications or client profiles, using a mouse or keyboard controls. It is the core of the Biofeedback and Psychophysiology monitoring setup.

The software has a multimedia-rich graphical user-interface, to capture and analyze raw data. Display sessions and script sessions are initiated to interface it with hardware and perform the measurements. There is also a database associated with it to capture the data streams and the compact flash terminal to remote relay the data log.

8. USB Receiver

A USB receiver is used to collect the remotely relayed signal streams from the flash recorder. It is connected to the USB port of PC. An installation setup is run before plugging it in. Placement depends on the orientation of the receiver ports and the transmitter antenna, which normally affects the performance.

Figure 3.12 USB Receiver

9. Alcohol wipes were used to clear the patch of skin for electrode placement.

Figure 3.13 Alcohol wipes used

3.4 sEMG data Collection/ Data Acquisition

The sEMG signals were recorded from the six muscles that involve in the flexion of knee and ankle, which are: Rectus Femora (RF), Vastus Lateralis (VL), Vastus Medialis (VM), Semitendinosus (ST), Tibialis Anterior (TA) and Gastrocnemius Medialis (GA).

The electrodes were placed on the dominant leg or the leg that shows a dominant response to walking and STS-induced stimuli. The placement of electrodes was configured according to the SENIAM guidelines (Hermens et al. 1999).

The electrodes were of silver-silver chloride triode structure, with a fixed inter-electrode distance of 2 cm and a diameter of 1cm (Thought Technology, Montreal, Quebec, Canada). The skin was cleaned by alcohol wipe before the placement of electrodes.

One of the examples of the sEMG electrodes connection for a participant during the experiment is shown in Figure 3.14. The sEMG signal was recorded by Flexcomp Infiniti encoder system and transmitted to a computer through Bluetooth wireless for display (Biograph Infiniti) at 2048 samples/sec.

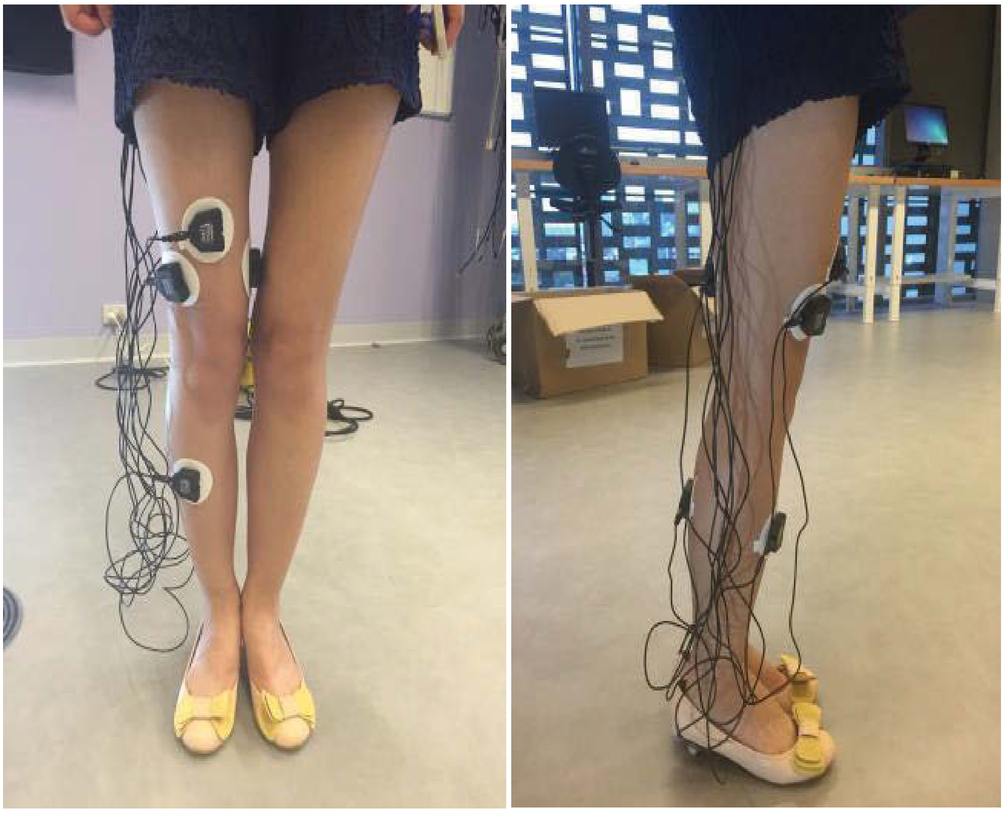


Figure 3.14 Electrodes connections for experiment

All tasks were performed in The Centre for Health Technology laboratory. The sequence of wearing different heights of shoes was randomly assigned. Detailed explanation and trials were given before data recording so that participants could familiarize themselves with the environment and procedure.

On completion of the setup, the Biograph Infiniti software was booted, then the impedance checking channel settings were selected. Once the channels were activated, the recording session is initialized.

3.5 Procedure - STS task

3.5.1 Flow Chart of steps involved in EMG data collection for STS task

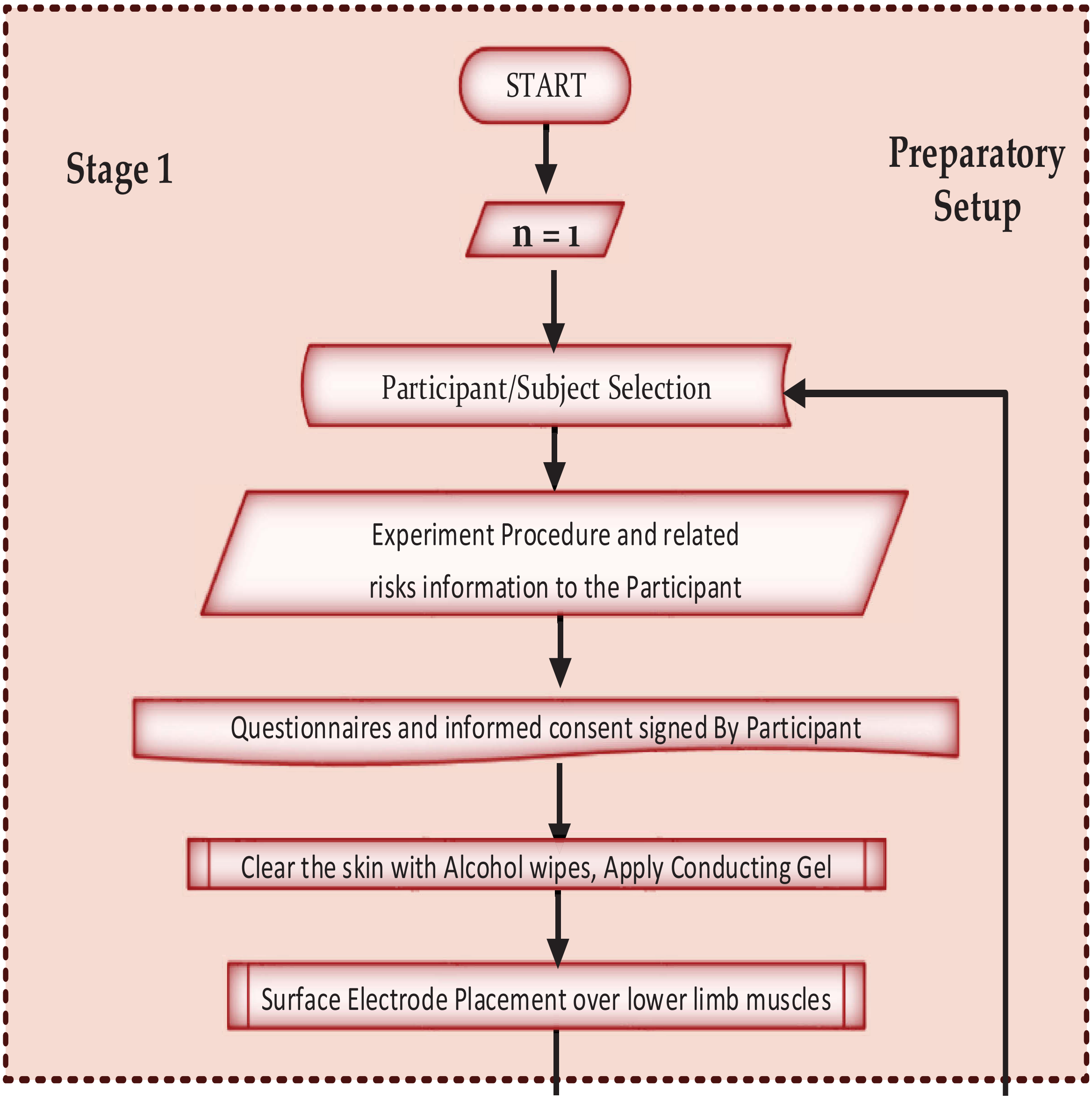


Figure 3.15 Flow chart of steps involved in EMG data collection for STS task ….

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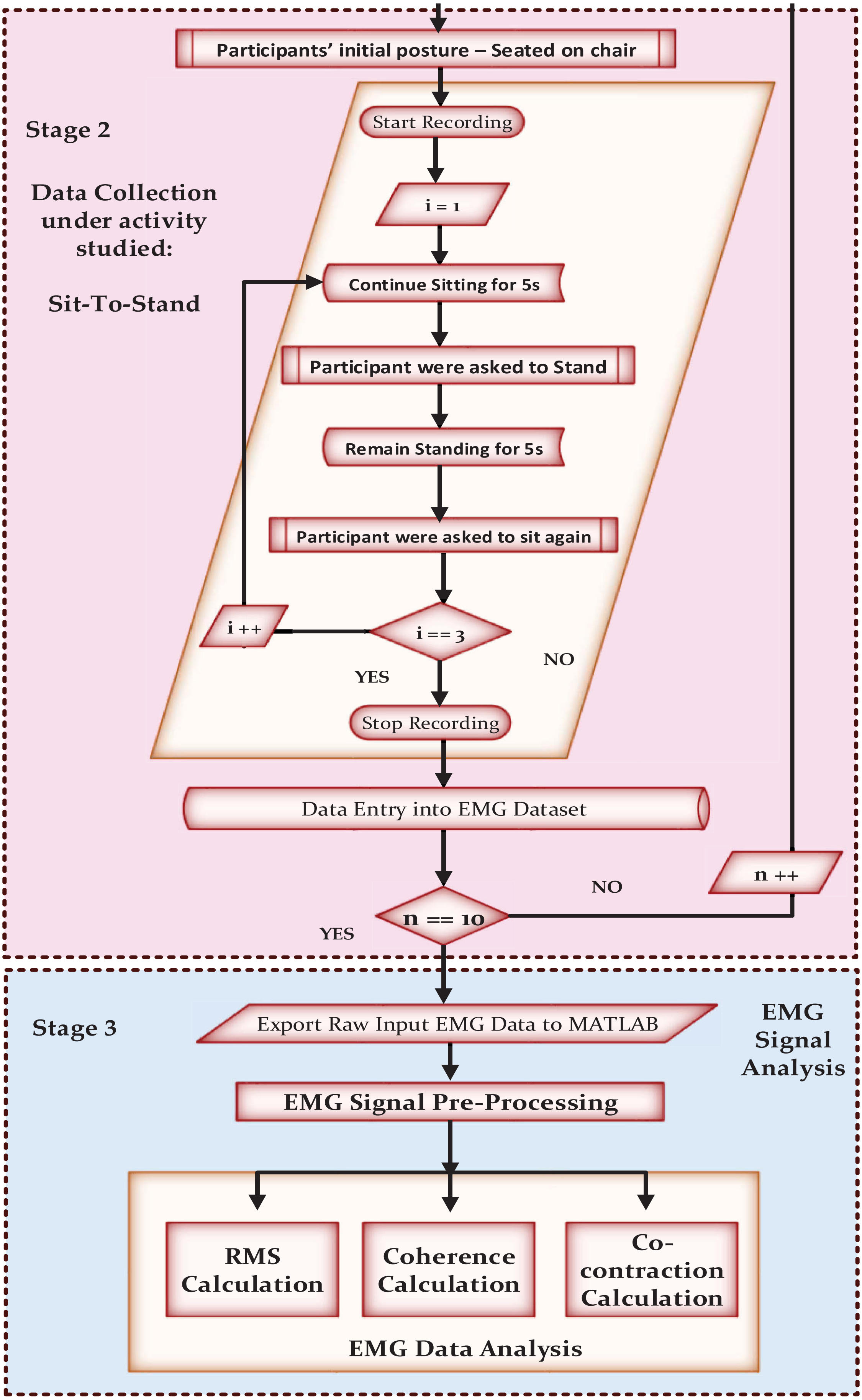

Stage 2
Data Collection under activity studied:
Sit-To-Stand
Participants' initial posture – Seated on chair
Start Recording
i = 1
Continue Sitting for 5s
Participant were asked to Stand
Remain Standing for 5s
Participant were asked to sit again
i ++
i == 3
NO
YES
Stop Recording
Data Entry into EMG Dataset
NO
n ++
YES
n == 10
Stage 3
Export Raw Input EMG Data to MATLAB
EMG Signal Analysis
EMG Signal Pre-Processing
RMS Calculation
Coherence Calculation
Co-contraction Calculation
EMG Data Analysis

3.5.2 Sample events during STS Task recording

1. Skin Preparation for the participant.

Figure 3.16 Skin Cleaning and applying conductive gel

2. Electrode placement.

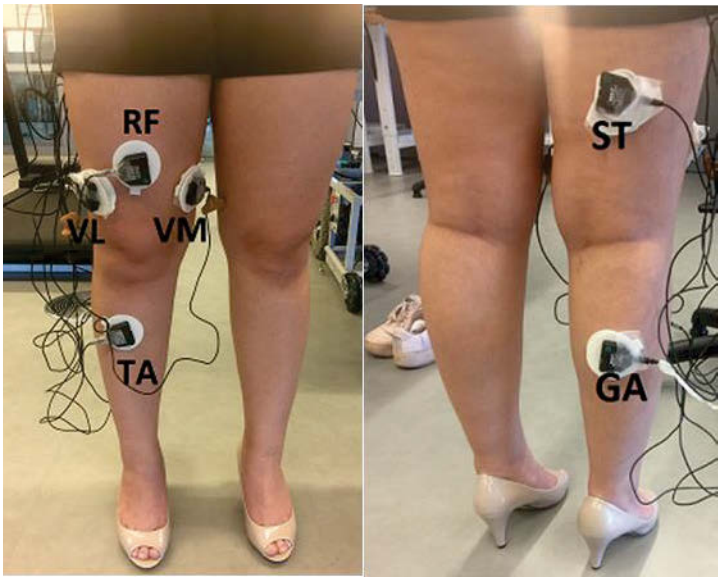


Figure 3.17 Electrode placement on lower limb muscles

3. Participants were asked to be seated on an adjustable armless and backless chair, with their feet separated at a comfortable distance. The seat heights were adjusted so that the hip and knee joint form nearly a right angle with the participants in a sitting position, before performing an STS task under different heel-height conditions. Participants were instructed to sit in a relaxed and comfortable position with their backs straight and their arms crossed and folded across their chest. They were asked to maintain a relaxed and comfortable seating position, as shown in Figure 3.18(a).

4. Data recording were started. After 5 seconds Participants were asked to rise from the chair when instructed verbally by the phrase “stand.” Refer Figure 3.18(b).

Figure 3.18 (a) Initial posture for STS (b) Sit-Stand Transition

5. Standing position and Stand-Sit Transition

Figure 3.19 Standing and Stand-Sit Transition

6. After 5s again they were asked to stand by the phrase "stand." This task was repeated three times. Participants were asked to maintain the standing posture for 5 seconds after completing the STS task. This STS task was performed at a self-selected speed.

Figure 3.20 Stand Again after 5 sec

3.6 Procedure - Walking Task

3.6.1 Flow chart of Steps involved in EMG data collection for walking task

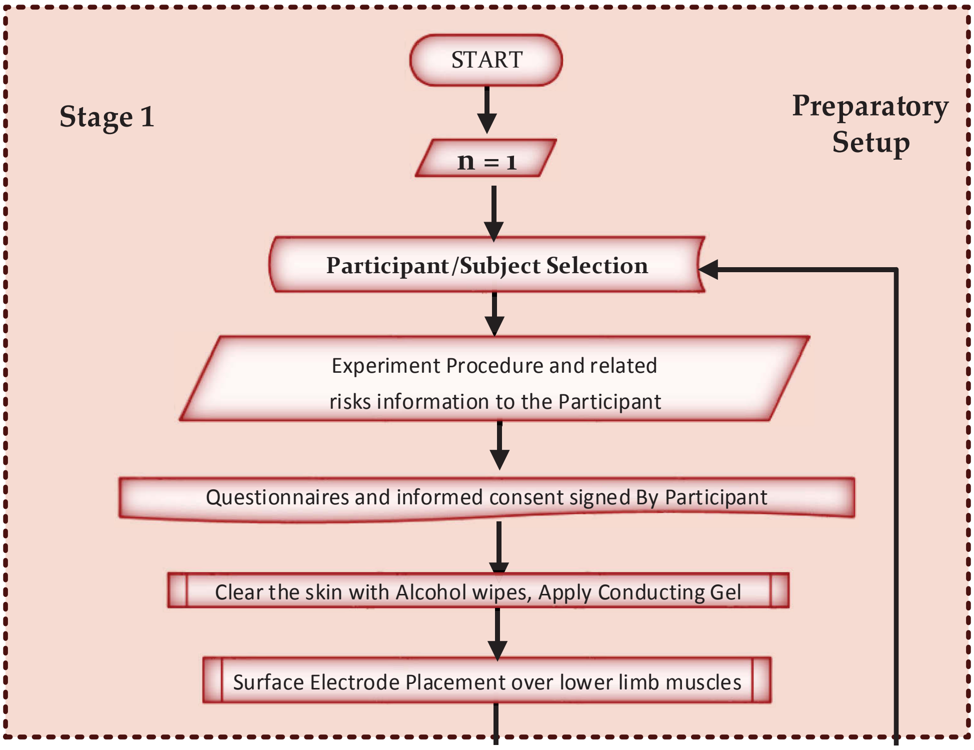
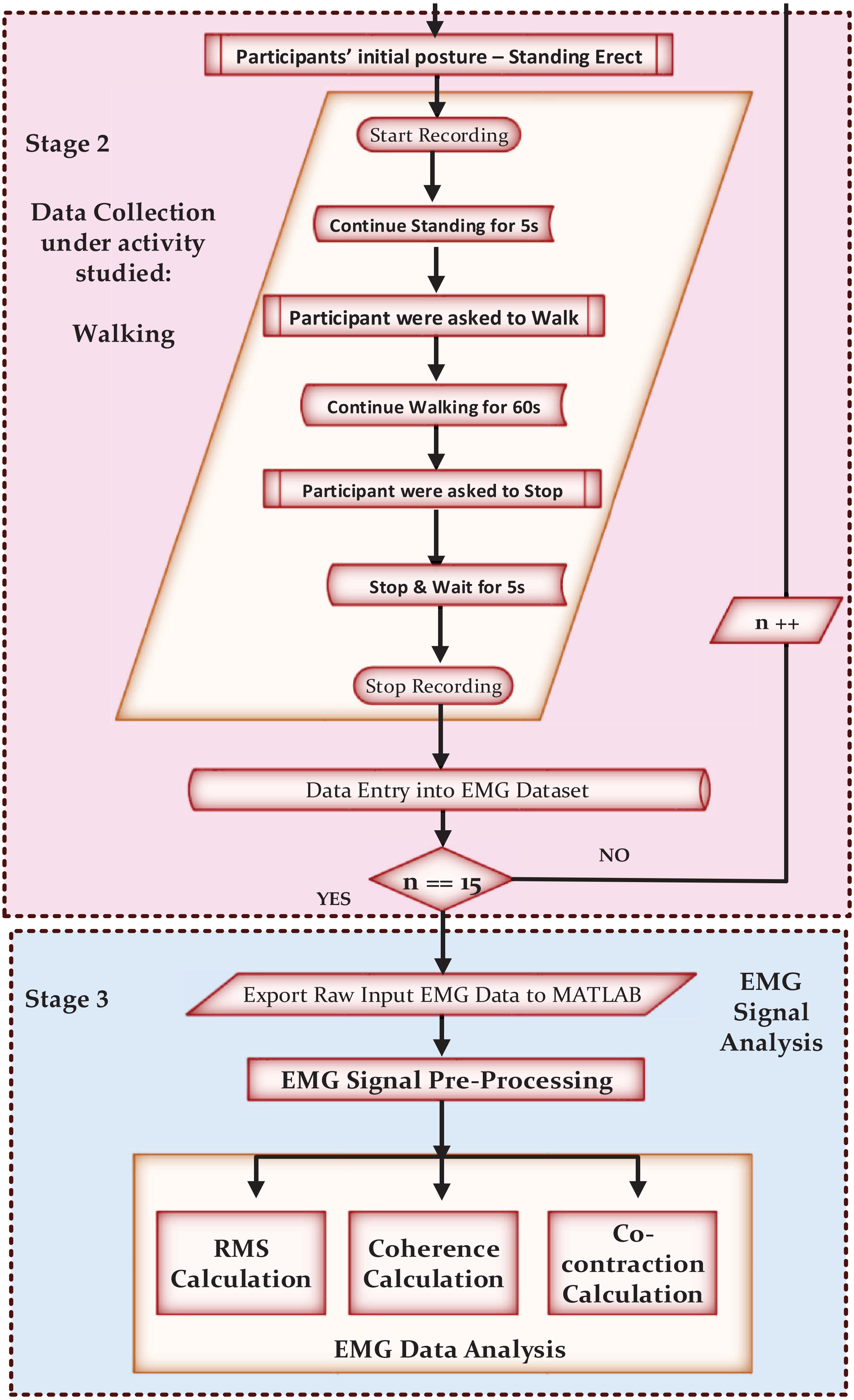


Figure 3.21 Flow chart of Steps involved in EMG data collection for walking task


Participants' initial posture – Standing Erect
Stage 2
Data Collection under activity studied:
Walking
Start Recording
Continue Standing for 5s
Participant were asked to Walk
Continue Walking for 60s
Participant were asked to Stop
Stop & Wait for 5s
n ++
Stop Recording
Data Entry into EMG Dataset
NO
n == 15
YES
Stage 3
Export Raw Input EMG Data to MATLAB
EMG Signal Analysis
EMG Signal Pre-Processing
RMS Calculation
Coherence Calculation
Co-contraction Calculation
EMG Data Analysis

3.6.2 Sample events during Walking Task recording

1. Skin preparation for the Participant

Figure 3.22 Skin Cleaning and applying conductive gel

2. Electrode Placement

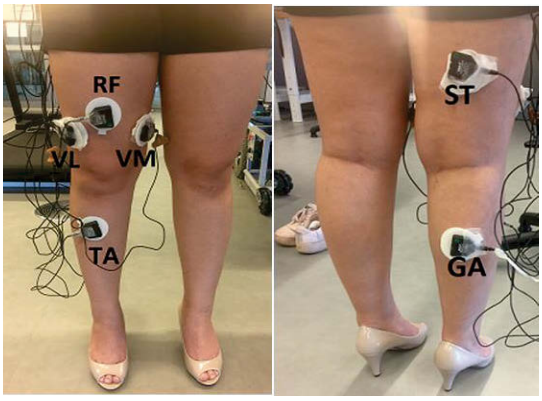


Figure 3.23 Electrode placement on lower limb muscles

3. In the initial posture, the subjects were required to stand upright with their weight equally distributed on both feet. Data recording were started.

Figure 3.24 initial posture for Walking Task

4. After 5 seconds in the initial posture, the subjects were asked to walk for 1 minute with their normal speed by signal phrase “start walking.” After one minute they were asked to stop by signal phrase “stop walking” and return to the initial posture.

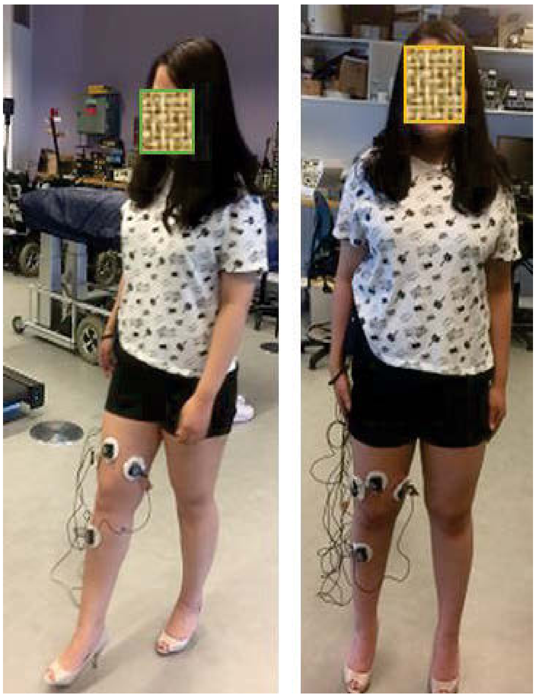


Figure 3.25 walking activity and Initial posture after one minute

5. Waited 5 seconds and stoped recording.

3.7 Data Processing

Data was exported from Biograph Infiniti interface and then processed using MATLAB R2015b software. In this research, sEMG data normalization was not mandated as participants were to behave according to their free will. All practices were executed within the same session window; hence electrode positions never required altering (Edwards et al. 2008; Soderberg & Knutson 2000).

A 4th order Butterworth band pass filter with a frequency range of 10 to 450 Hz was applied to reject any frequency outside this range, which is likely to be noise. A sample Raw EMG data of walking task and STS task data are shown in Figure 3.26 and Figure 3.27.

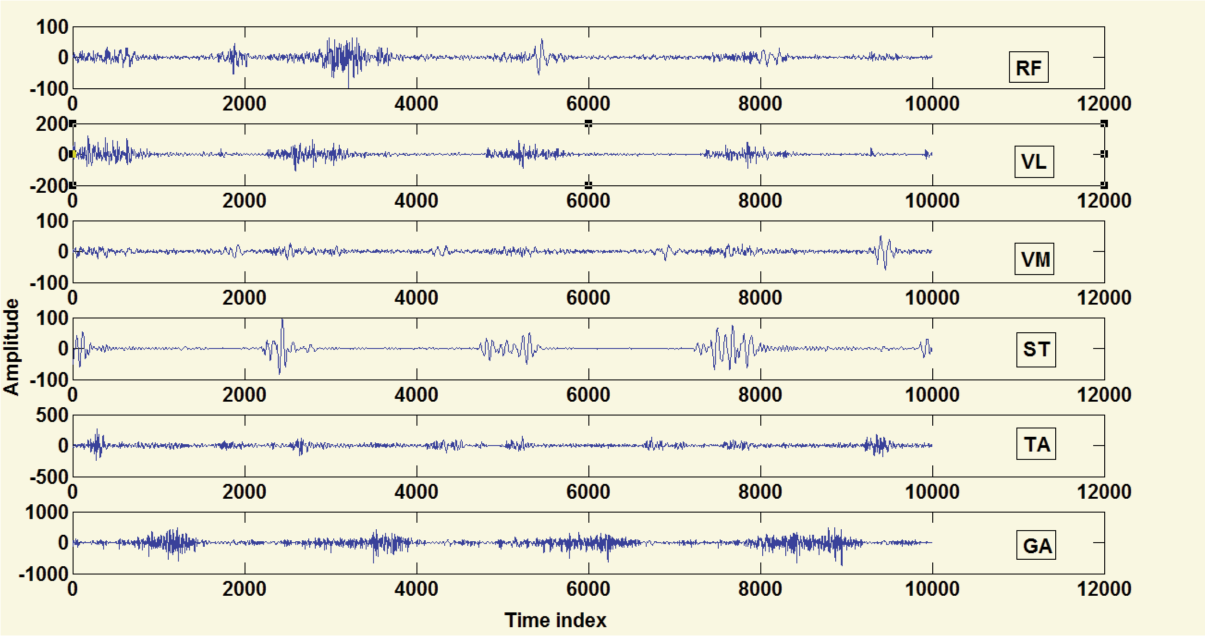


Figure 3.26 Extracted raw EMG data sample for all six muscles for 5 seconds during walking task

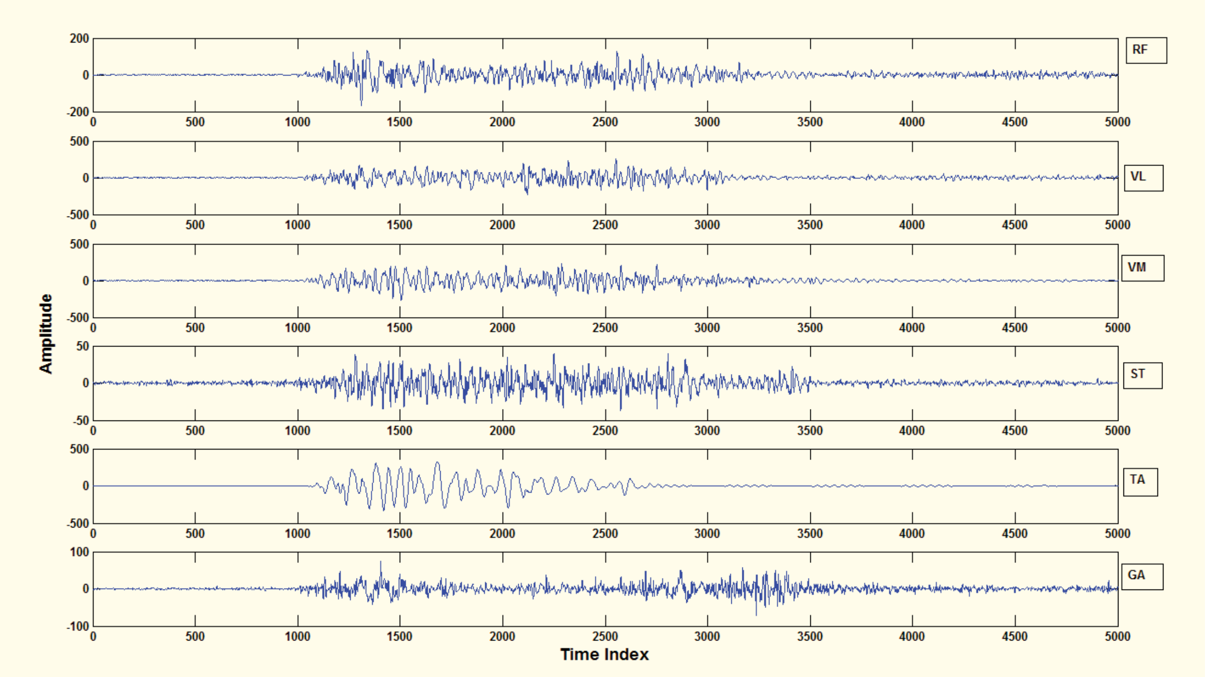


Figure 3.27 Extracted raw EMG data sample of all six muscles for one trial STS task

3.8 EMG Data Analysis

3.8.1 RMS

To assess the effect of heel height on walking and STS tasks, we computed the RMS feature from the complete STS and walking data. Before that, the muscle activity onset timestamp of each muscle was defined as the point at which the amplitude of signal exceeded the mean amplitude plus three times standard deviations (SD) during the 1s interval before the start of the walking and STS tasks. Root mean square (RMS) feature was calculated for a moving window of 500ms.

Computation:

The RMS measure is obtained as:

$$\text{RMS}=\sqrt{\frac{1}{N}\sum_{n=1}^{N}|x(n)|^2} \tag{1}$$

Where, $x(n)$ = recorded/segmented EMG signal at time n

n = time index of recorded EMG signal

N =Total number of samples to be analyzed

The results of the above parameter were averaged separately over all participants for each heel height for each task. This is known as the Pooled results.

The STS task is relatively much short in duration (around 15 seconds per trial), as compared to the walking task (70 seconds). Thus, in order to get more accurate values and a better representation of the changes and signal patterns, the average RMS of three trial has been calculated and considered as the corresponding reading for each subject.

Statistical Analysis:

A repeated measures analysis of variance (ANOVA) was carried out to determine statistically significant differences between the different heel heights. Significance level for each interpretation was fixed at $p < 0.05$ (95% confidence intervals).

3.8.2 Co-Contraction

Muscle co-contraction was assessed between the quadriceps (RF, VL, and VM) and hamstring (ST) muscle pairs, which include VL – ST, VM – ST and RF – ST combinations. The CCI provided a measure of relative activation of the muscle pairs at each instance of the gait cycle (Hubley-Kozey, Deluzio & Dunbar 2008; Lewek, Rudolph & Snyder-Mackler 2004). The co-contraction index (CCI) is computed by integrating the ratio of the linear-enveloped EMG multiplied by the sum of the EMG magnitudes for the quadriceps and hamstring muscle pairs as described by Nelson-Wong et al. (2012).

Computation:

$$CCI = \sum_{i=1}^{N}\left(\frac{EMG_{low_i}}{EMG_{high_i}}\right)\left(EMG_{low_i} + EMG_{high_i}\right) \tag{2}$$

where N is the total number of data points for the time frame of interest,

EMG_{lowi} is the lower EMG value at the ith data point,

EMG_{highi} is the higher EMG value at the ith data point.

During the analysis, Equation 2 was applied to the sEMG data of each muscle pair (VL-ST, VM-ST, and RF-ST) that was recorded for both tasks. For each i^{th} point, the linear-enveloped EMG magnitudes were compared by taking the ratio of the low over the high value and then multiplied by the sum of the two magnitudes (Equation 2). These products were then summed over all data points.

The above procedure was repeated for all HHS for both tasks and the all subjects. The results of the above parameter were averaged separately over all participants (pooled results) for each heel height for each task.

As explained in section 3.7.1, STS task is of very short duration. Hence, to get more accurate results & analysis, the average Co-Contraction of three trials is considered as the corresponding reading for each subject.

Statistical Analysis:

One way analysis of variance (ANOVA) test was performed to compare the CCI calculated for each of the three muscle pairs (RF-ST, VM-ST, and VL-ST) using different heel heights. The statistical level of significance was fixed at $p < 0.05$ (95% confidence intervals).

3.8.3 Coherence

Common oscillatory drive to a muscle pair was quantified by EMG-EMG coherence (Wang et al. 2015). It was calculated using Welch's periodogram method with a Hamming window of 2,048 samples and overlap of 1,024 samples (Wang et al. 2015). Coherence assigns a unit less real number between 0 to 1; larger values (closer to 1) corresponds to two signals are perfectly coherent or synchronized in the frequency domain; smaller values (closer to 0) indicate that the two EMG signals are not coherent.

Computation:

The Coherence was calculated for RF-VL, RF-VM and RF-ST muscle pairs using the following equation (Wang et al. 2015).

$$C_{ab}(f) = \frac{|S_{ab}(f)|}{S_{aa}(f) * S_{bb}(f)} \tag{3}$$

Where, $\mathrm{S_{ab}(f)}$ is cross spectra and $\mathrm{S_{aa}(f)}$,

$\mathrm{S_{bb}(f)}$ are the auto spectra of a (t) and b (t).

The above procedure was repeated for all HHS for both tasks and the all subjects. The results of the above parameter were averaged separately over all participants (pooled results) for each heel height for each task.

Because STS task is a very short duration (section 3.7.1), more accurate analysis and better interpretations are obtained through the average coherence of three trials taken as the corresponding reading for each subject.

Statistical Analysis:

One way analysis of variance (ANOVA) with repeated measure was performed to compare the Coherence calculated for each of the three muscle pairs (RF-VL, RF-VM, and RF-ST) using three different heel heights. Significance level for each interpretation was fixed at $p < 0.05$ (95% confidence intervals).

3.9 Summary

The experimentation chapter showcases the design adopted, protocols set and computational analysis performed on the Datasets under study. The detailed procedure for real-time EMG data harvest, with the regulations in place for compliance, were first explained. The Procedure includes laboratory measurement trials using Thought Technology Ltd. EMG analysis equipment set, and performing the defined mathematical and statistical operations for obtaining significant results. This contributes to validating the proposed hypothesis on the Raw EMG Data collected.

The inclusion-exclusion criteria, laboratory & experiment environment standards have been clearly defined for future references, as well as the various preset regulations for ideal data collection and investigations.

Chapter 4 : **Results and Discussions**

4.1 Outline of the chapter

This chapter presents the key contributions of this research project – the **hypotheses** extended with their verification, concluding on attaining the research aims.

The first sections elaborate on the RMS analysis of lower limb muscle activity for STS and walking tasks while wearing high heel shoes. It is followed by the corresponding discussion of observed results for each task. Thus Hypothesis 1 and Aim 1 of research is confirmed.

The following section explores the Co-contraction analysis of lower limb muscles for STS and walking task while wearing high heel shoes. Then, combined discussion for both task has been explained. This section demonstrates the Hypothesis 2 and Aim 2 of this research.

In the Last section, Coherence analysis of lower limb muscles for STS and walking task, while wearing high heel shoes, has been presented. It continues towards the combined discussion for both tasks. Hypothesis 3 and Aim 3 of this research are thus characterized.

4.1.1 Mind Map

The Mind Mapping of the presented concepts, inferences, and unique contributions are outlined in the structure below.

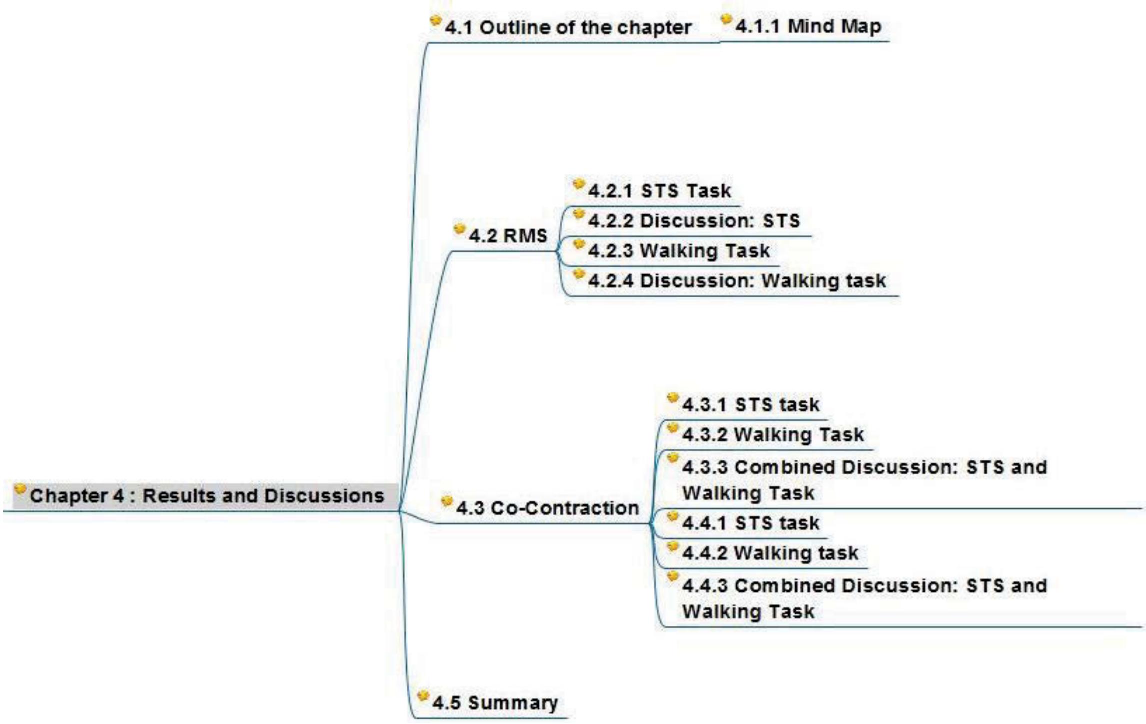


Figure 4.1 Results and Discussion – Section Structure

4.2 RMS

MATLAB Implementation of RMS (Root Mean Square) based EMG analysis has been organized for the lower Limb muscle activation patterns during Sit to Sand (STS) and Walking tasks on different high-heeled shoes. The Results were given valid interpretation based on relevant EMG literature and MATLAB implementation.

4.2.1 STS Task

The average pooled results for RMS during STS task is shown in Figure 4.2. Similarly, the utilization of each muscle (in percentage) during STS task for all heel heights is shown in Figure 4.3. RMS results (Figure 4.2) shows that as the heel height increases sEMG activity is increasing in all muscles. Also, there is a significant increase of VM values for elevated heel heights, whereas a moderate increase of muscle activities is visible in readings from other muscles.

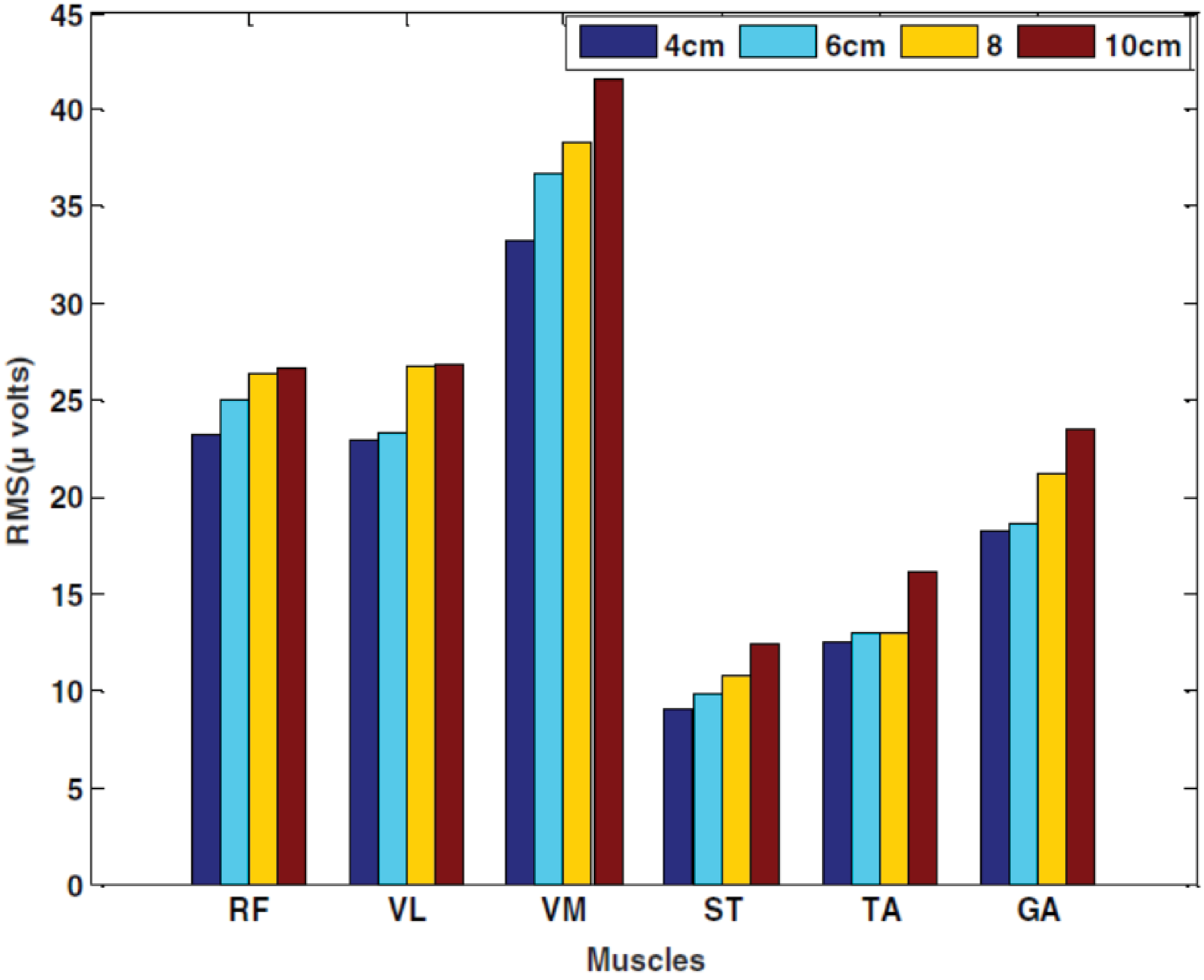


Figure 4.2 Pooled RMS plots showing each muscle activities for four different heel heights during STS task.

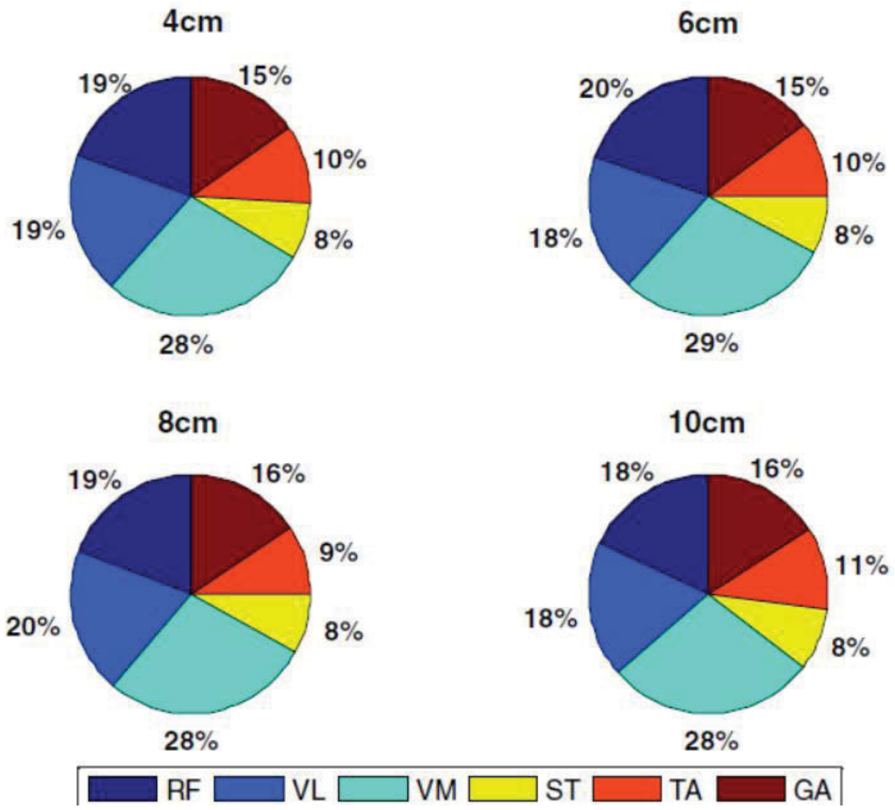


Figure 4.3 Muscle utilization (percentage) factor in STS task for different heel heights

Overall (in terms of RMS results), increasing heel height caused increases in sEMG activities (RMS) for all the muscles. The statistical analysis (ANOVA) results showed that results are statistically significant ($p<0.05$).

Overall muscle utilization factor (refer to Figure 4.3) results indicate that VM is utilized almost 1/3rd of the entire muscle utilization followed by RF and VL (nearly 1/5th). This indicates that quadriceps muscles activate more for STS tasks (65%) as compared to hamstring (ST) and calf muscles (GA) in women.

RMS Study on STS task has been published in EMBC Conference.

4.2.2 Discussion: STS

According to Williams and Haines (Williams & Haines 2014),the quadriceps muscles are activated more to prevent knee collapse. Hence, the increased quadriceps muscle activities (seen in this study) have served to compensate for the tendency to flex the knee when performing the STS task.

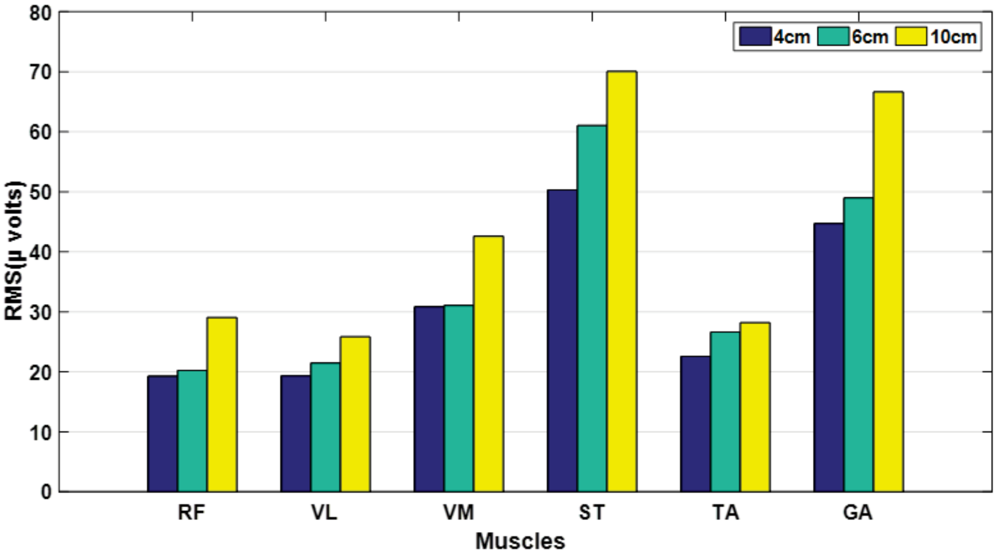


Figure 4.4 Pooled RMS plots showing each muscle activities for three different heel heights during walking task

4.2.3 Walking Task

The average pooled results for RMS during Walking is shown in Figure 4.4. Similarly, the utilization of each muscle (in percentage) during walking task for all heel heights is shown in Figure 4.5. RMS results (Figure 4.4) shows that as the heel height increases sEMG activity is increasing in all muscles.

Also, there is a significant increase of ST and GA values for elevated heel heights, whereas a moderate increase of muscle activities is noted in other muscles. All together (concerning RMS results), increasing heel height caused increases in sEMG activities (RMS) for all the muscles.

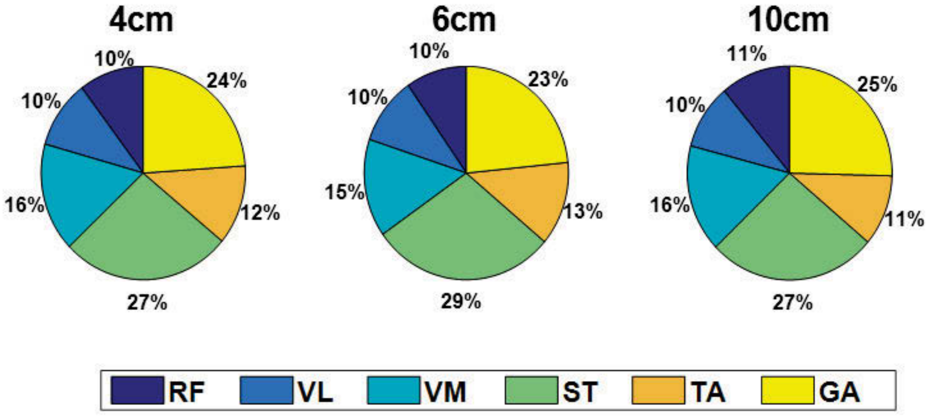


Figure 4.5 Muscle utilization (percentage) factor in walking task for different heel height

The statistical analysis (ANOVA) results showed that results are statistically significant ($p<0.05$).

Overall muscle utilization factor (refer to Figure 4.5) results indicate that combined ST and GA are utilized almost 50% of the all muscle utilization followed by VM and TA (nearly 30% combined). This indicates that hamstring (ST) and calf muscle (GA) activates more in walking tasks (50%) as compared to quadriceps muscles (35%), and hence contribute more towards maintaining stance and posture.

4.2.4 Discussion: Walking task

Falling while walking on the high heeled shoe is prevented by Hamstring and Calf muscle, through increases in their activation (Ishikawa, Pakaslahti & Komi 2007; Srivastava, Mishra & Tewari 2012). Maintaining balance and stability in the human body is brought about by different kinematic and biomechanical changes in our lower limbs while walking high heel shoes. Such changes depend on factors like walking speed, muscle length, muscle tension, etc. (Lee 2011; Woollacott & Pei-Fang 1997). To avoid imbalance, falling, and instability while walking on high heel shoes, lower limb muscles compensate their activities, which in turn stabilizes the muscle activation patterns, irrespective of heel height (Lloyd & Buchanan 2001; Woollacott & Pei-Fang 1997).

All these studies have inspected the physiological or other similar perspectives into muscle activity adaptations under such external stimuli. The investigation performed within this project embraces the EMG Signal analysis perspective and corroborates the findings mentioned above.

4.3 Co-Contraction

MATLAB Implementation of Co-Contraction based EMG analysis has been done for lower Limb muscle pair synchronization patterns during Sit-to-Sand (STS) and Walking tasks on different high-heeled shoes. Results and interpretation were carried out based on noteworthy Co-contraction literature and MATLAB implementation.

The Co-contraction study based analysis and inferred findings on STS task have have been composed as a Journal article and been submitted to Biomedical Engineering Online Journal.

4.3.1 STS task

Pooled (mean and standard deviation) CCI from the four heel heights for the three muscle group combinations is shown in Figure 4.6. The highest CCI ratio was found for the VM-ST muscle pairs, while the lowest values were found for RF-ST and VL-ST variants. The results indicated that the CCI ratios increased for elevated HHS, this is because both quadriceps and hamstrings muscles exert higher abduction and/or adduction moments for high-level muscle activities (Lloyd & Buchanan 2001; Palmieri-Smith et al. 2009).

Also, due to increased mechanical demands associated with STS tasks, it is reasonable to expect activation of the lower limb muscles to increase with HHS (Seyedali et al. 2012a). Predominantly, simultaneous recruitment of muscles that produce moments in opposite directions and increased antagonistic muscle co-contraction around the joint has a substantial influence on the movement patterns of the knee during STS task (Sirin & Patla 1987).

The distribution of muscle involvement (quadriceps and hamstring) in the different HHS - STS tasks, as measured by the CCI ratio (percentage of each muscle pair) are shown in Figure 4.7. From the results, it can be interesting to see that RF-ST, VL-ST, and VM-ST showed similar CCI distribution (approximately 34%, 28% and 38% respectively) irrespective of heel height.

In other words, the CCI distribution remains constant for RF-ST, VL-ST, and VM-ST for all HHS. This is due to the fact that both quadriceps and hamstring muscles have the potential to provide dynamic frontal-plane knee stability and have the capacity to balance variable abduction-adduction loads (Lloyd & Buchanan 2001; Palmieri-Smith et al. 2009).

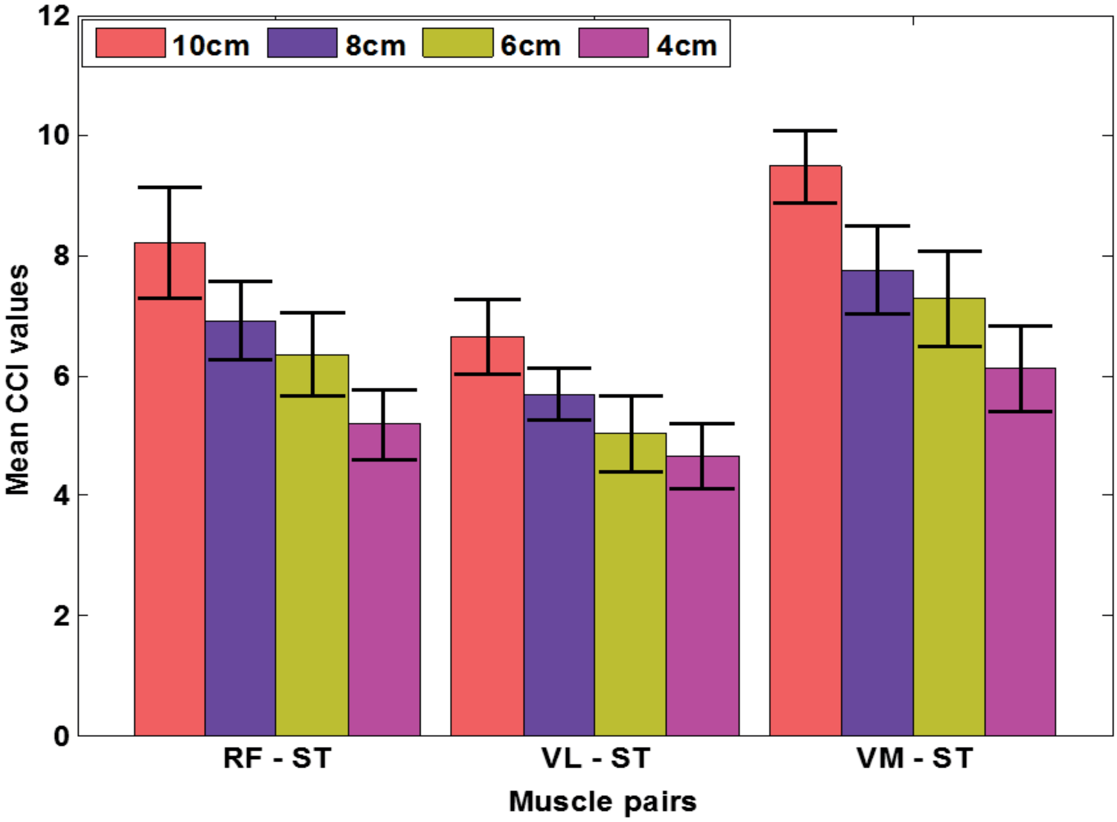


Figure 4.6 The mean and standard deviation of CCI from the four heel heights for three muscle group combinations.

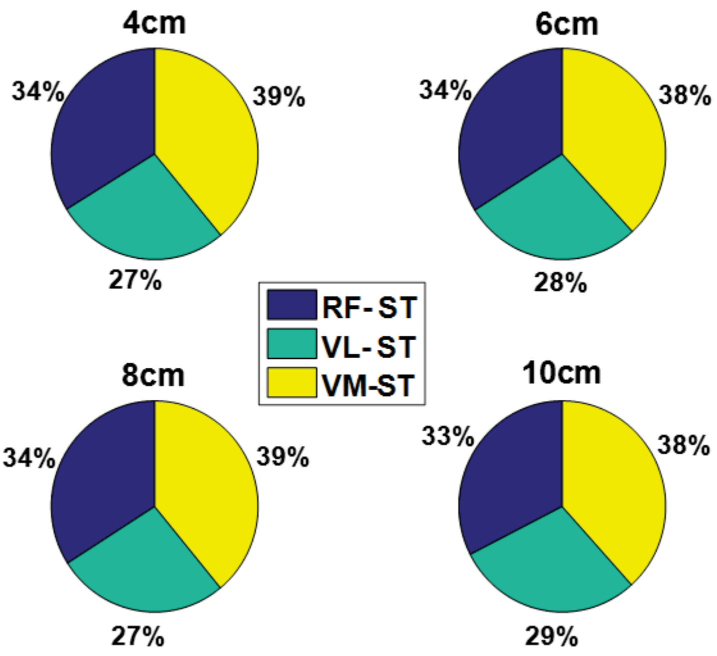


Figure 4.7 The CCI distribution for RF-ST, VL-ST, and VM-ST for all heel heights.

4.3.2 Walking Task

Pooled (mean and standard deviation) CCI from the three heel heights for the three muscle group combinations is shown in Figure 4.8. The highest CCI ratio was found for the VM-ST muscle pairs, while the lowest values were found for VL-ST and RF-ST variants.

The results indicated that the CCI ratios increased for elevated HHS, this is due to the fact that both quadriceps and hamstrings muscles put more effort for high-level muscle activities (Lloyd & Buchanan 2001; Palmieri-Smith et al. 2009). Also, due to increased mechanical demands associated with walking tasks, lower limb muscle activities are expected to increase with HHS (Ishikawa, Pakaslahti & Komi 2007; Srivastava, Mishra & Tewari 2012).

Predominantly, simultaneous recruitment of muscles that produce moments in opposite directions and increased antagonistic muscle co-contraction around the joint has a substantial influence on the movement patterns of the knee during the walking task (Ishikawa, Pakaslahti & Komi 2007; Srivastava, Mishra & Tewari 2012).

The distribution of muscle involvement (quadriceps and hamstring) in the different HHS - walking tasks, as measured by the CCI ratio (percentage of each muscle pair) are shown in Figure 4.9. From the results, it can be interesting to see that RF-ST, VL-ST, and VM-ST showed similar CCI distribution (approximately 27%, 34%, and 39% respectively) irrespective of heel height. In other words, the CCI distribution remains constant for RF-ST, VL-ST, and VM-ST for

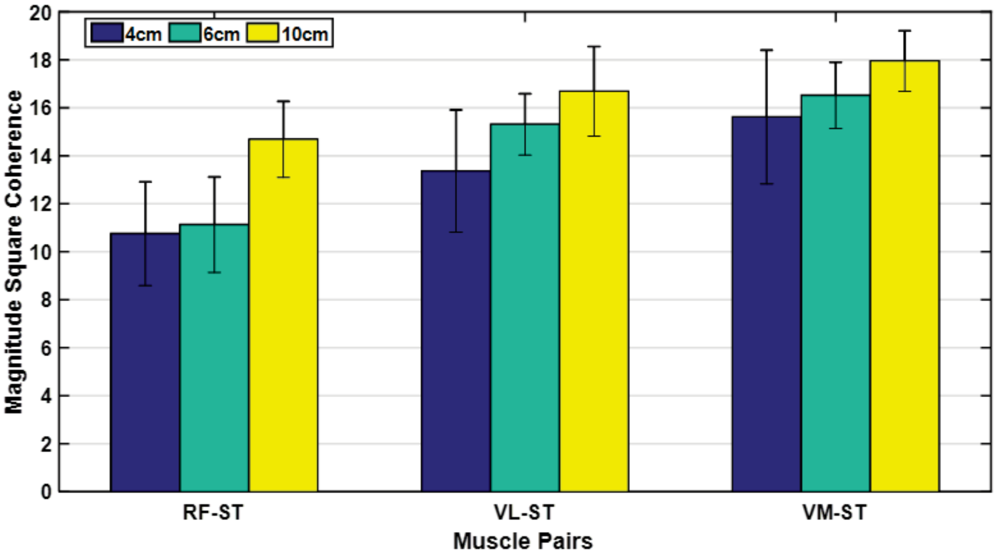


Figure 4.8 The mean and standard deviation of CCI from the four heel heights for three muscle group combinations during Walking Task.

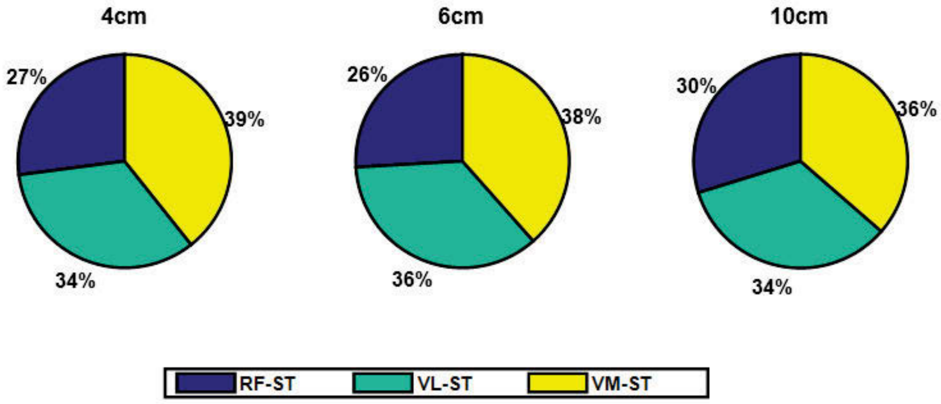


Figure 4.9 The CCI distribution for RF-ST, VL-ST and VM-ST for all heel heights during walking task

all HHS. This is due to the fact that both quadriceps and hamstring muscles have the potential to provide dynamic plane knee stability and have the capacity to balance during unstable walking condition (Besier et al. 2009).

4.3.3 Combined Discussion: STS and Walking Task

As stated in (Seyedali et al. 2012b), it is unclear whether increased activation of lower limb agonist and antagonist (quadriceps and hamstring) muscles is relatively equal or not, directly influencing co-contraction levels.

An understanding of how quadriceps and hamstring muscles behave during STS and walking can help clarify the motor control strategies exerted through the medium of muscle excitation patterns to overcome excessive muscle co-contraction. (Goulart & Valls-Solé 2001) reported the differential action of related muscles during the STS task. They conclusively stated that the pattern of muscle activity remained constant when the initially seated posture changed.

Under unstable conditions, to ensure stability around the knee joint, the quadriceps and hamstring muscles increase their co-contraction level during walking. This set of muscles also stabilize the pattern of muscle pair synchronization continuously (Besier et al. 2009). As stated by (Seyedali et al. 2012b) Co-contractions may represent a limb stiffening strategy to enhance stability during phases of initial heel strike for HHS, which may result in increasing CCI values for elevated HHS.

Same muscle utilization factor regarding quadriceps to hamstring ratio is observed for all heel heights (Refer to Figure 4.7 & 4.9). Hypothetically, the combined influence provided by both quadriceps and hamstring muscles should be approximately constant under different co-contraction levels, since CCI ratio remains the same for all HHS heights.

Hence, it is evident that elevated HHS exert a greater amount of external work in order to maintain the same quadriceps to hamstring ratio as compared to lower HHS. It also makes the irrefutable point that elevated HHS movements allow the muscle to perform more work over the pre-defined STS and walking activities (from the experiment protocol) compared to lower HHS movements. This act has been theoretically deduced by previous literature.

Another discovery made here is that for elevated shoes, if co-contraction increases, both quadriceps and hamstring muscles can compensate the resultant stress onto the limbs. The above results are also in agreement with previous studies stating that due to muscle redundancy, various neuro-motor strategies may exist to compensate for excessive muscle co-contraction during STS and walking in an unstable condition such as walking on high heel shoes (Alkjær et al. 2012; Wang & Gutierrez-Farewik 2014).

STS and Walking tasks demand optimum neuromuscular coordination and postural changes to control and prevent loss of body balance and posture (Barton, Coyle & Tinley 2009; Besier et al. 2009; Cronin, Barrett & Carty 2012; Joseph 1968; Lee 2011; Srivastava, Mishra & Tewari 2012; Woollacott & Pei-Fang 1997). According to previously conducted research, the role of maintaining postural balance in the human body needs necessary adjustments in muscle operation (Dehail et al. 2007).

One publication reported that the regular usage of high heel shoes for walking, STS, and related tasks might contribute to changes in body posture, which then may induce low back pain in women (Barton, Coyle & Tinley 2009).

Our research findings indicated that the capacity of quadriceps and hamstring muscles to compensate externally induced muscle stress is fundamental for retaining normal STS and walking task performance. It manifests into relatively higher muscle co-contraction for elevated HHS.

In other words, the experimental results point out that women appear to co-contract their muscles in real-time as a means of enhancing stability and support while undergoing sit-t-stand and walking motion with HHS. Under such conditions, women may employ co-contraction strategies also to stabilize and provide extra shock absorption during the heel strike.

4.4 Coherence

MATLAB Implementation for coherence analysis has been done for lower limb muscle synchronization during STS and walking tasks for different high-heeled shoes. Results and interpretation were carried out based on valid literature from Coherence studies and MATLAB implementation.

The Coherence investigation performed on walking task-based EMG observations has been submitted to Journal for Healthcare Technology Letters.

4.4.1 STS task

Figure 4.10 shows Beta Band coherence analysis of all three-muscle pairs (RF-VL, RF-VM, and RF-ST) for one of the participants for all heel heights. The mean and standard deviation of Beta Band coherence values of all muscle pairs for different HHS for STS are given in Table 4.1

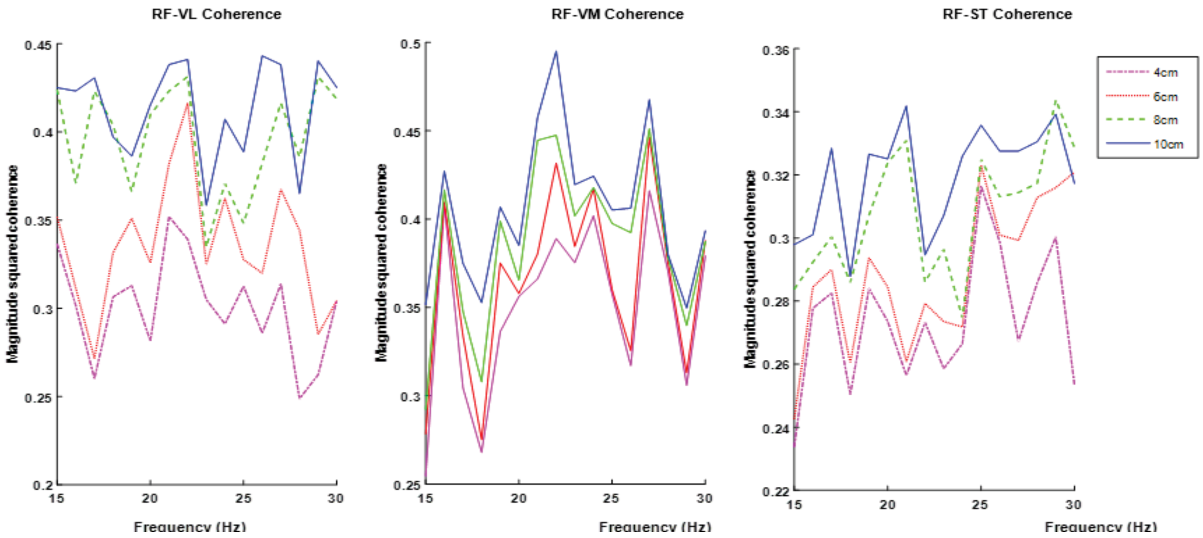


Figure 4.10 One-participant Beta Band (15-30Hz) coherence values for RF-VL, RF-VM, and RF-ST muscle pairs, during STS on High heeled shoes

Average Beta Band (15-30Hz) coherence values for RF-VL, RF-VM and RF-ST muscle pairs, during STS on 4cm, 6cm, 8cm and 10 cm shoes is shown in Fig. 4.12. From the results, it is noticeable that Beta Band coherence value was significantly increasing ($p<0.05$) during STS in RF-VL, RF-VM and RF-ST muscle pairs for all HHS

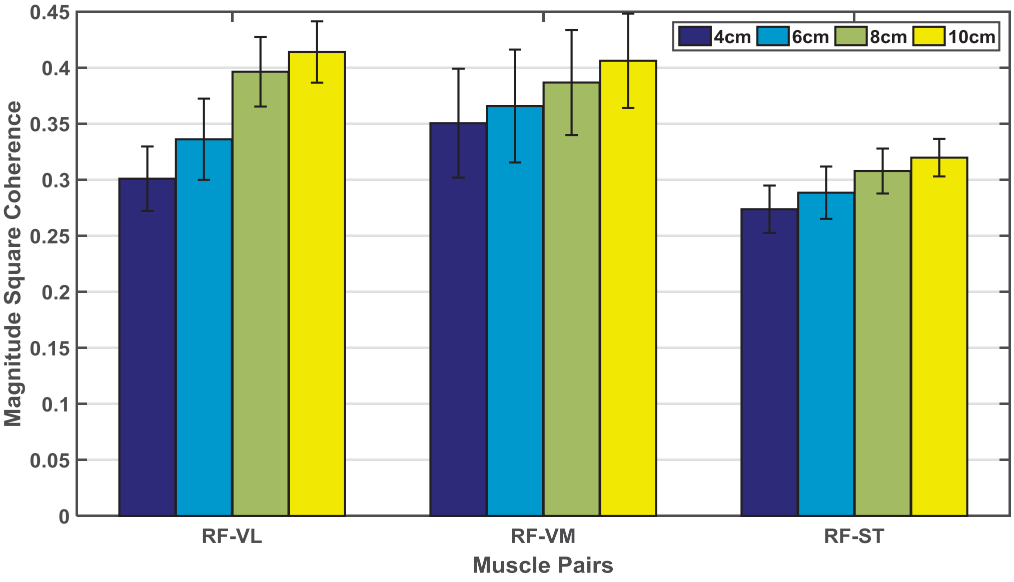


Figure 4.11 Average Beta Band (15-30Hz) coherence values for RF-VL, RF-VM, and RF-ST muscle pairs, during STS task

Table 4.1 Average Beta Band (15-30Hz) coherence values of all muscle pairs for different HHS during STS

Muscle Pair	**4cm**	**6cm**	**8cm**	**10cm**
RF-VL	0.3009±0.0288*	0.3360±0.0362*	0.3963±0.0310*	0.4139±0.0274*
RF-VM	0.3504±0.0486*	0.3657±0.0503*	0.3867±0.0469*	0.4060±0.0421*
RF-ST	0.2736±0.0211*	0.2884±0.0234*	0.3077±0.0201*	0.3196±0.0167*

*Significant at $p < 0.05$

4.4.2 Walking task

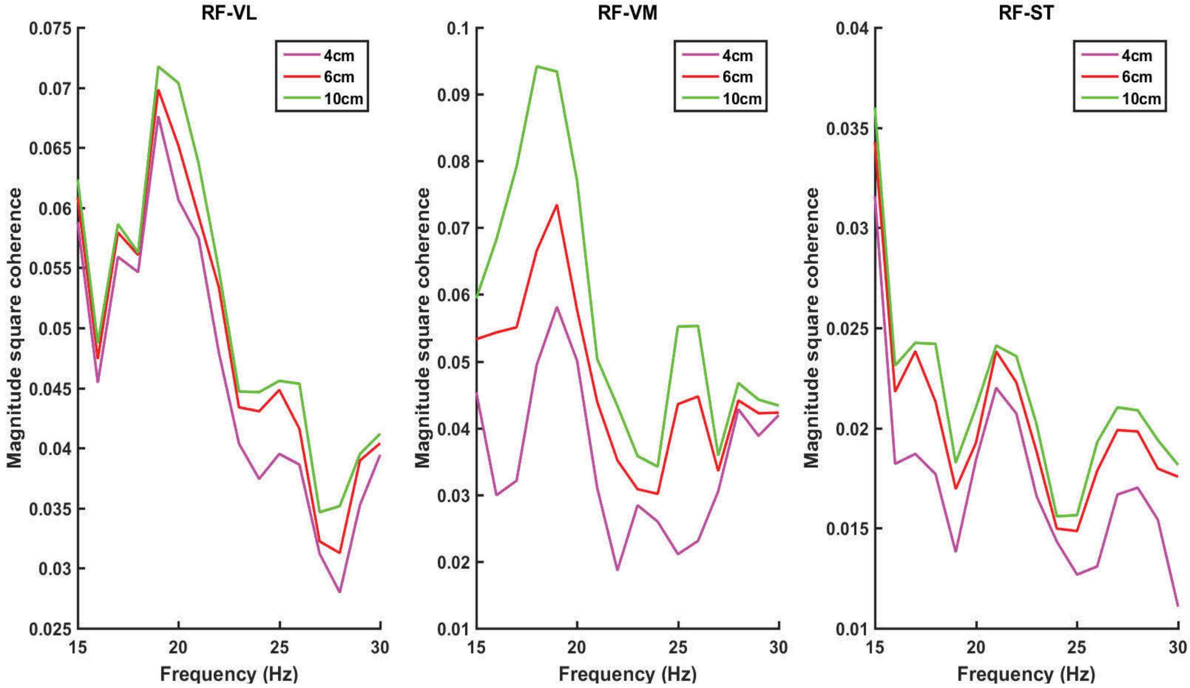


Figure 4.12 Beta Band (15-30Hz) coherence values for RF-VL, RF-VM and RF-ST muscle pairs in one participant, during self-paced walking on 4cm, 6cm and 10cm heels shoes.

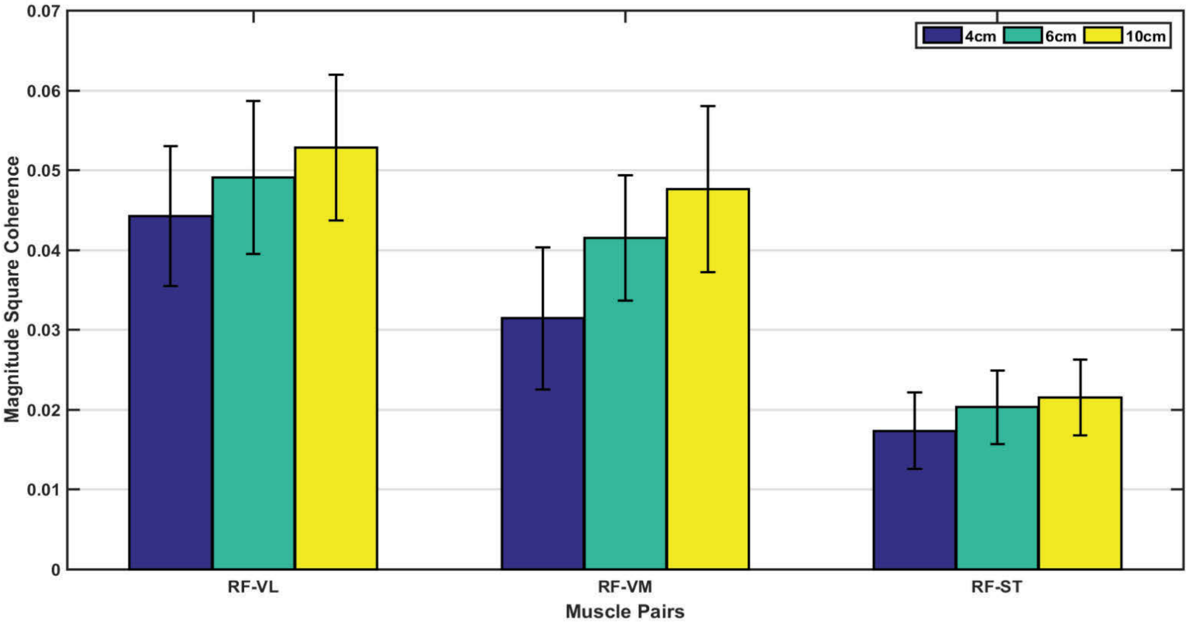


Figure 4.13 Average Beta Band (15-30Hz) coherence values for RF-VL, RF-VM, and RF-ST muscle pairs, during self-paced walking on 4cm, 6cm and 10cm heels shoes.

Table 4.2 Average Beta Band (15-30Hz) coherence values of all muscle pairs for different HHS during walking

Muscle Pair	4cm	6cm	10cm
RF-VL	0.0442±0.0088*	0.0491±0.0096*	0.0529±0.0091*
RF-VM	0.0315±0.0089*	0.0415±0.0079*	0.0477±0.0104*
RF-ST	0.0174±0.0048*	0.0203±0.0046*	0.0215±0.0048*

*Significant at p < 0.05

Figure 4.12 shows Beta Band coherence analysis of all three-muscle pairs (RF-VL, RF-VM, and RF-ST) for one of the participants for all heel heights. The mean and standard deviation of Beta Band coherence values of all muscle pairs for different HHS for walking are given in Table 4.2.

Average Beta Band (15-30Hz) coherence values for RF-VL, RF-VM and RF-ST muscle pairs, during walking on 4cm, 6cm and 10cm heels shoes is shown in Fig. 4.13.

From the results, it can be seen that Beta Band coherence value was significantly increasing ($p<0.05$) during walking in RF-VL, RF-VM and RF-ST muscle pairs for all HHS.

4.4.3 Combined Discussion: STS and Walking Task

Coherence study aimed at unearthing the changes in lower limb muscle synchronization – regarding patterns - during STS and walking on HHS. Previous studies found out that some kinematic modifications in knee movement occur while walking on HHS, which involve changes in the lower limb muscle activities (Opila-Correia 1990b). If there is any such change in muscle functioning, then a corresponding adaptation of in muscle-pair synchronization must exist, which is not well identified yet for STS and walking in HHS.

During STS and walking movements, the quadriceps and hamstring muscles are mainly responsible for maintaining balance around the knee (Levangie & Norkin 2011). EMG-EMG coherence is a good measure to analyze this sort of muscle synchronization. In this study, results obtained point towards significantly higher Beta Band coherence during STS and walking in HHS for all muscle pairs. That implies at higher degrees of muscle pair synchronization being required for walking and STS on heel shoes to maintain body balance. According to previous research, higher Beta Band coherence was found under fatigue conditions of the lower limb muscles (McManus et al. 2016; Wang et al. 2015).

From coherence study segment of this research, it can be concluded that STS and walking in HHS increases Beta Band coherence. The inference is that the lower limbs require more muscle synchronization to avoid imbalance around the knee, as these muscles coordinate in action for maintaining knee balance by compensating their activation pattern together. The fact is a direct authentication of the discovery made in (Levangie & Norkin 2011).

Concluding from the coherence study results for walking & STS combined, we suggest that, in pursuance of stability around the knee, the following physiological events occur:

1. The lower limb muscles necessitate short-term plastic changes in the neural drive while walking on HHS. Plasticity is the ability of motoneurons and their respective effector muscles to change physically and functionally as a result of environmental conditions, activity, age, and other factors (Gransee, Mantilla & Sieck 2012).
2. Higher Coherence value reflects on an adjusted neural strategy of the peripheral-nervous system to control muscles during high-heeled walking. The most likely functional role of muscle synchronization that will be in play under such conditions is the motor-unit synchronization. The effect will actualize as an increase in the rate of force development during rapid contractions or a mechanism to coordinate the activity of multiple muscles (Semmler 2002).

4.5 Summary

This chapter has explored the results and relevant discussions of three hypothesis of this research, which can be summarized as follows:

- Lower limb muscles activate in a specific pattern , which remains constant in all heel height in both tasks by increasing their muscle activity.
- Regardless of the task, strength of antagonistic muscle pair synchronization pattern or their strength of coordination pattern remain same in all heel height by increasing their co-contraction level.
- Common drive to synergistic muscle pair increased with elevated heel hight in both tasks.

The proposed study evidence and interpretations are conducted on a short-term time scale. Based on results, it is inferred that the lower limb muscles have the ability to adjust with external-environment changes during a Walking and STS task on HHS to prevent falling and imbalance. These adjustments are the higher muscle activity, enhanced the strength of muscle pair synchronization and increased common neural oscillation.

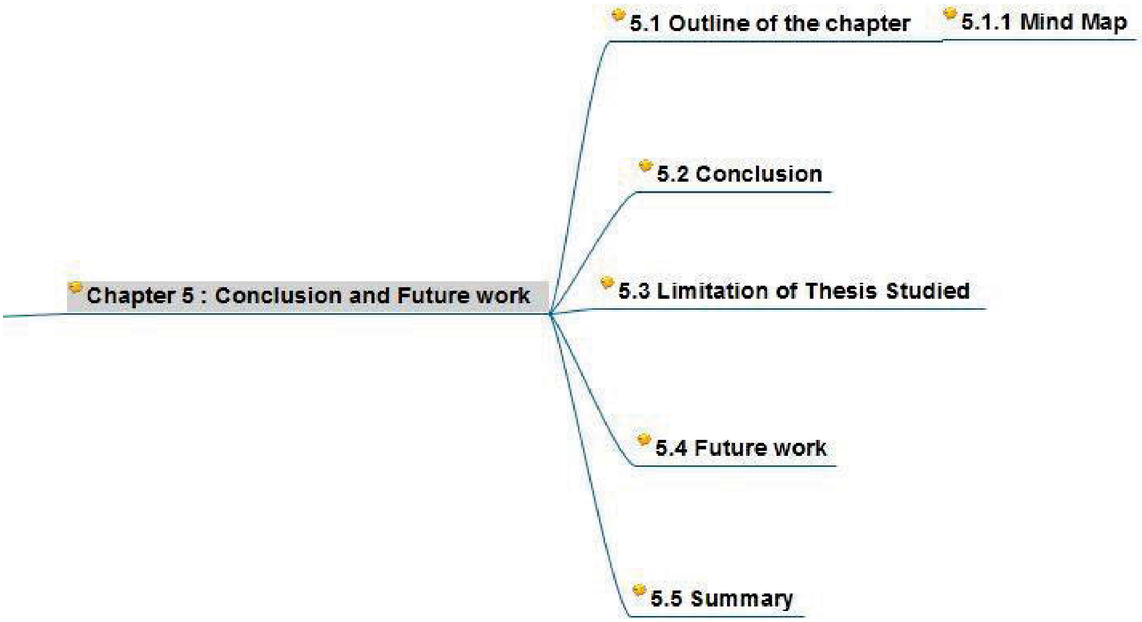
Chapter 5 : **Conclusion and Future work**

5.1 Outline of the chapter

This chapter draws all relevant conclusions on the length of the study under this thesis. The highlights are the realistic limitations that materialized while performing our research, as well as the scope of future work and further development of concepts.

5.1.1 Mind Map

Below is the mind map of the chapter.



5.2 Conclusion

This study has produced useful information on the effects of heel height on muscle activation and muscle pair synchronization during STS and Walking tasks. Based on the findings of this research, it can be concluded that:

- Irrespective of the task involved in, lower limb muscle activation and muscle pair synchronization increase with elevated heel height
- Irrespective of heel height in use, muscle utilization factor and CCI distribution of all three antagonistic muscle pair remains same in two different task.

- The results of this study support the thesis statement that irrespective of task performed (Walking and STS) muscle activation pattern and muscle pair synchronization pattern remain constant by compensation strategies of lower limb muscles.

We also suggest that the long-term muscle activation, synchronization and adaptation behaviors will contradict short-term plastic changes. As is the general nature of any body part or organ, prolonged application of external stimuli will aggregate the effects on our body. The resultant physiology-oriented characteristics will vary permanently on a large scale from the generic nature. For instance, a permanent (daily basis) heel shoe-user, will experience stress and hence plastic adaptation strategies along the muscles we studied while wearing flats or a much smaller heel.

Based on physiological and biological muscular system characteristics, we also suggest that frequent Walking and STS tasks under long-term use habits of HHS may induce the imbalance and instability around a joint. Knee pain, ankle pain, ankle twist, and different other leg injuries will happen.

5.3 Limitation of Thesis Studied

The main limitations of our study are based on age range and physiology, based on the fact that the subjects were representative of a population of young women – they constitute the most frequent users of HHS, which is the objective of our hypothesis. Hence, the findings of this research may not be generalized to females in all age groups.

Another significant factor, which is heavily constrained under laboratory investigations, is the Body-Mass Index ranges and Health Indices. The BMI cannot be matched with gross measures of the global population, as it varies with geography, climate, social and cultural backgrounds. From our various inferred ideas as well as previously validated facts, it is safe to assume that such factors will reflect on physiological behavior. However, to pick representative candidates for tuning all such parameters within a two-year research period under such a study scope is impossible.

If not as critical as the BMI limitation, health index of the participants also varies, on a larger as well as much smaller scale. Often, participants might not be transparent about their physiological status. Again, finding candidates to symbolize such variations is also hard. Further effects may also come from other factors like the menstrual cycle, genetic traits, etc.

5.4 Future work

The lower limb muscles study included in this dissertation is suggested only for a short-term basis, demonstrating body balance initiatives through muscle-activation pattern adjustments. Long-term changes induced by habitual HHS usage requires further investigation and may vary from or such muscle properties.

Section 5.3 has enumerated the assumptive constraints for ideal laboratory investigation. Therefore, future works involving a large number of participants (both young and old) are necessary to confirm these hypotheses. Also, deeper investigations of the influence of the muscle forces on elevated heel heights are obligatory. Any such studies by relaxing the parameters fixed throughout the experiment will add on to the knowledge.

Some of the valid future directions, as identified during the course of this study, are listed below:

1. Extend the current research for longer HHS walking period.
2. Study of the difference in muscle activity of ankle stabilizing muscles when wearing high-heeled shoes with different heel width.
3. Investigation under similar conditions, where the pace and direction are varied in each heel height.
4. Study the effect of HHS under walking on non-planar or uneven surfaces.
5. Similar study where the data is characterized in terms of time periods, with subjects showing similar time-window of behavior.
6. Research analysis with regular wearers of a particular heel height to see the difference in muscle activity between the groups.
7. Extended research into the activity of the Erector Spinae, Gluteus Maximus and Abdominal muscles.
8. There are some indications that the fibularis longus muscle has less endurance to fatigue in women who regularly wear high-heeled shoes as compared to non-regular wearers (Gefen, 2002). In our study, the participants only had to walk for under a minute in each heel height. The rise in muscle activity after a whole day (> 5 hours) of walking in high-heeled shoes will bring a lot more different perspectives into muscle-limb coordination.
9. The results obtained from this research can be exploited to reduce medical problems due to the high-heeled shoes.

The next level of further research is to look into patterns or rather multi-variate measures among the different muscle activations. These are defined as activation patterns or adaptation-patterns. Different multi-modal computational techniques allow extracting patterns or higher order relationships between more than one variable (in this case, different data streams referring to different muscles studied, whose combined pattern is to be derived).

Synergy is a common measure of muscle adaptation strategies of a group of muscles combined, to perform any task. It is a single element modeling more than one elemental (muscle) behavior for synchronization and activation. Hence, Synergy is the simplest definition of activation or adaptation patterns in muscle operation.

Synergistic behavior can be extracted using Non-Negative Matrix Factorization approach, where changes in the synchronization pattern of all six muscles, which were studied here, can be observed, during the defined tasks with HHS (Torres-Oviedo & Ting 2007).

Connectivity analysis is the inspection of muscle networking or rather correlating positively or negatively the excitation of lower limb muscles using EMG signals. It is also significant as a measure of muscle activity patterns (Boonstra et al. 2015).

5.5 Summary

Due to extensive use of high heel shoes by many women and its side effects, there is need to understand the strategies and changes of lower limb muscle activation and muscle pair synchronization to induce the balance. This thesis works in the direction to achieve the research aim by using the relevant methodology and analysis. To prevent from falling and imbalance, irrespective of the two task studies (Walking and STS) lowe7r limb muscles activate and synchronized with another muscle in a pair in a fixed specific pattern, which is maintained by increasing their activity, the strength of coordination and common neural oscillation.

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