

T.C.
BAHCESEHIR UNIVERSITY
GRADUATE SCHOOL
DEPARTMENT OF BIOMEDICAL ENGINEERING

**ANALYSIS OF GAIT SYMMETRY USING EMG DATA ACROSS
DIFFERENT SPEEDS**



MASTER'S THESIS
ÇAĞLA TUNÇ SAVAŞ

ISTANBUL 2025

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ABSTRACT

Analysis of Gait Symmetry Using EMG Data Across Different Speeds

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Master's Program in Biomedical Engineering

Advisor: Asst. Prof. Bora Büyüksaraç

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The aim of this study is to examine how gait symmetry (left and right leg muscle activation) changes at different speeds using available surface electromyography (sEMG) data of the tibialis anterior, gastrocnemius medialis, soleus, vastus lateralis and biceps femoris muscles. 25 healthy individuals participated in the study and walked at 13 different walking speeds ranging from 2.9 km/h to 7.2 km/h, and 50 walking cycles were recorded at each speed. Two separate data sets were created from the obtained data, namely feature-based (feature matrix) and time-series-based (percentile matrix), and the symmetry index (SI) was calculated from both data sets.

The symmetry index (SI) values calculated both feature-based and time-series-based were compared at different walking speeds and statistically evaluated. The findings revealed that there was a significant decrease in the symmetry index as the walking speed increased, indicating that muscle activation symmetry improved. This tendency was particularly evident in the tibialis anterior, gastrocnemius medialis and vastus lateralis muscles; the soleus muscle showed more stable symmetry at all speeds due to its postural role. The biceps femoris attracted attention by showing high variation at the closest speed to natural walking speed.

This study demonstrates that not only the general speed effect, but also muscle-based neuromuscular responses should be considered in the assessment of gait symmetry, providing a meaningful scientific basis for clinical and performance-based applications.

Key Words: Gait Symmetry, Walking Speed, Surface Electromyography (sEMG), Symmetry Index (SI), Muscle Activation Patterns



ÖZET

Farklı Hızlarda EMG Verileri Kullanılarak Yürüyüş Simetrisinin Analizi

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Bu çalışmanın amacı, tibialis anterior, gastrocnemius medialis, soleus, vastus lateralis ve biceps femoris kaslarına ait mevcut yüzey elektromiyografi (sEMG) verileri kullanarak yürüyüş simetrisinin (sol ve sağ bacak kas aktivasyonu) farklı hızlarda nasıl değiştiğini incelemektir. Çalışmaya katılan 25 sağlıklı birey, 2.9 km/s ile 7.2 km/s arasında değişen 13 farklı yürüyüş hızında yürümüş; her bir hızda 50 yürüyüş döngüsü kaydedilmiştir. Elde edilen verilerden öznitelik temelli (feature matrix) ve zaman serisi temelli (percentile matrix) olmak üzere iki ayrı veri seti oluşturulmuş, her iki veri seti üzerinden simetri indeksi (SI) hesaplanmıştır.

Hem öznitelik bazlı hem de zaman serisi bazlı olarak hesaplanan simetri indeksi (SI) değerleri, farklı yürüyüş hızlarında karşılaştırılmış ve istatistiksel olarak değerlendirilmiştir. Bulgular, yürüyüş hızı arttıkça genel olarak simetri indeksinde anlamlı bir azalma olduğunu, yani kas aktivasyon simetrisinin iyileştiğini ortaya koymuştur. Bu eğilim, özellikle tibialis anterior, gastrocnemius medialis ve vastus lateralis kaslarında belirginleşmiş; soleus kası postüral rolü nedeniyle her hızda daha stabil simetri göstermiştir. Biceps femoris kası doğal yürüme hızına en yakın hızda yüksek varyasyon sergileyerek dikkat çekmiştir.

Bu çalışma, yürüyüş simetrisinin değerlendirilmesinde sadece genel hız etkisinin değil, kas bazlı nöromüsküler yanıtların da dikkate alınması gerektiğini ortaya koymakta, klinik ve performans temelli uygulamalar için anlamlı bir bilimsel zemin sunmaktadır.

Anahtar Kelimeler: Yürüyüş Simetrisi, Yürüme Hızı, Yüzey Elektromiyografi (sEMG), Simetri İndeksi (SI), Kas Aktivasyon Paternleri

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TABLE OF CONTENTS

ETHICAL CONDUCT	III
ABSTRACT	IV
ÖZET.....	VI
ACKNOWLEDGEMENTS	VII
TABLE OF CONTENTS	viii
LIST OF TABLES	xi
LIST OF FIGURES.....	xiii
LIST OF ABBREVIATIONS	xviii
Chapter 1 Introduction	1
1.1 Background.....	1
1.2 Statement of the Problem	3
1.3 Purpose of the Study.....	3
1.4 Hypotheses / Research Questions.....	3
1.5 Significance of Study	4
1.6 Definitions	4
Chapter 2 Literature Review	5
2.1 The Importance of Gait Symmetry and the Use of EMG.....	5
2.2 Gait Symmetry: Current Research.....	6
2.3 Targeted Muscles and Their Functions	12
2.3.1 Tibialis anterior	12
2.3.2 Gastrocnemius medialis	12
2.3.3 Soleus	12
2.3.4 Biceps femoris.....	13
2.3.5 Vastus lateralis	13
2.4 Walking Phases	13
2.4.1 Stance phase.	13
2.4.2 Swing phase.....	14
2.5 Gait Symmetry Analysis Using EMG Data.....	15
2.6 Effect of Speed on Gait Symmetry.....	17
2.7 Rationale For Methodological Selection	18

Chapter 3 Methodology.....	20
3.1 Study Design And Participants.....	20
3.2 Instruments And Devices	20
3.2.1 EMG	20
3.2.2 XSSENS	20
3.3 Data Acquisition.....	23
3.3.1 EMG.....	23
3.3.2 XSSENS	23
3.4 Experimental Protocol	23
3.5 Data Analysis.....	24
3.5.1 Feature extraction from emg data.....	25
3.5.2 Feature selection.....	25
3.6 Outlier Detection	26
3.7 Data Structure	27
3.7.1 Feature matrix (Size: 16,250 x 71).....	28
3.7.2 Percentile matrix (Size: 16,250 x 501).....	29
3.8 Analyzing Symmetry Using EMG Data.....	29
3.8.1 Calculate symmetry for the feature matrix.....	30
3.8.2 Calculate symmetry for the percentile matrix	31
3.9 Statistics.....	31
3.10 Speed - Symmetry Index Correlation Analysis	31
Chapter 4 Results	33
4.1 Outlier Removal	33
4.2 Feature-Based Symmetry Analysis Across Walking Speeds	42
4.2.1 MAV feature	42
4.2.2 AR feature	49
4.2.3 RMS feature	55
4.3 Frame-Based Symmetry Analysis Across Waking Speeds	63
4.4 Correlation Between Speed and Symmetry Index.....	77
Chapter 5 Discussion.....	83
5.1 Summary and Interpretation of General Findings	83
5.2 Comparison of Gait Symmetry Analysis Findings - Feature and Frame Based....	83
.....	83

5.2.1	MAV feature analysis.....	83
5.2.2	AR feature analysis	86
5.2.3	RMS feature analysis	88
5.2.4	Comparison between features and overall evaluation.....	90
5.2.5	Frame-Based symmetry analysis.....	91
5.3	Correlation Between Speed and Symmetry Index.....	92
Chapter 6 General Conclusion, Limitations & Future Work		96
6.1	Conclusion	96
6.2	Limitations & Future Work	97
REFERENCES.....		99

LIST OF TABLES

TABLES

Table 1 Mean Symmetry Index and Standard Deviation Values Before Outlier Removal (25 Participants)	41
Table 2 Mean Symmetry Index and Standard Deviation Values After Outlier Removal (12 Participants).....	41
Table 3 Mean and Standard Deviation of Symmetry Index Values in Each Muscle at Different Walking Speeds – MAV Feature Analysis.....	42
Table 4 Symmetry Index Differences Across Walking Speeds for Tibialis Anterior Muscle – Post Hoc Results (MAV Feature, Speed: km/h)	45
Table 5 Symmetry Index Differences Across Walking Speeds for Gastrocnemius Medialis Muscle – Post Hoc Results (MAV Feature, Speed: km/h).....	47
Table 6 Symmetry Index Differences Across Walking Speeds for Vastus Lateralis Muscle – Post Hoc Results (MAV Feature, Speed: km/h)	48
Table 7 Mean and Standard Deviation of Symmetry Index Values in Each Muscle at Different Walking Speeds – AR Feature Analysis.....	50
Table 8 Symmetry Index Differences Across Walking Speeds for Biceps Femoris Muscle – Post Hoc Results (AR Feature, Speed: km/h)	53
Table 9 Mean and Standard Deviation of Symmetry Index Values in Each Muscle at Different Walking Speeds – RMS Feature Analysis.....	55
Table 10 Symmetry Index Differences Across Walking Speeds for Tibialis Anterior Muscle – Post Hoc Results (RMS Feature, Speed: km/h).....	60
Table 11 Symmetry Index Differences Across Walking Speeds for Vastus Lateralis Muscle – Post Hoc Results (RMS Feature, Speed: km/h).....	62
Table 12 Mean and Standard Deviation (Mean $\pm$ SD) of Symmetry Index Values in Each Muscle at Different Walking Speeds -Frame Based	63
Table 13 Symmetry Index Differences Across Walking Speeds for the Gastrocnemius Medialis Muscle – Post Hoc Results (Frame-based, Speed: km/h)	69
Table 14 Symmetry Index Differences Across Walking Speeds for the Soleus Muscle – Post Hoc Results (Frame-based, Speed: km/h)	71

Table 15 Symmetry Index Differences Across Walking Speeds for the Vastus Lateralis Muscle – Post Hoc Results (Speed: km/h).....	75
Table 16 Correlation Results Between Walking Speed and Symmetry Index Based on MAV Feature.....	78
Table 17 Correlation Results Between Walking Speed and Symmetry Index Based on AR Feature.....	79
Table 18 Correlation Results Between Walking Speed and Symmetry Index Based on RMS Feature	80
Table 19 Correlation Results Between Walking Speed and Symmetry Index Based on Frame.....	81

LIST OF FIGURES

FIGURES

Figure 1 The Gait Cycle/Walk Cycle (Bergamini et al., 2024).....	1
Figure 2 Delsys Trigno wireless EMG system (Halabi et al., 2019)	21
Figure 3 Xsens sensor plugged into Awinda station (MTw Awinda User Manual, 2018)	22
Figure 4 Delsys trigger module (Delsys Incorporated, n.d.)	22
Figure 5 Distribution of mean symmetry index and standard deviation values across speeds for the Tibialis Anterior muscle in 25 participants	33
Figure 6 Distribution of mean symmetry index and standard deviation values across speeds for the Gastrocnemius Medialis muscle in 25 participants	34
Figure 7 Distribution of mean symmetry index and standard deviation values across speeds for the Soleus muscle in 25 participants.	34
Figure 8 Distribution of mean symmetry index and standard deviation values across speeds for the Vastus Lateralis muscle in 25 participants	35
Figure 9 Distribution of mean symmetry index and standard deviation values across speeds for the Biceps Femoris muscle in 25 participants	35
Figure 10 Distribution of mean symmetry index and standard deviation values across speeds for the Tibialis Anterior muscle in 12 participants after outlier removal	36
Figure 11 Distribution of mean symmetry index and standard deviation values across speeds for the Gastrocnemius Medialis muscle in 12 participants after outlier removal.	36
Figure 12 Distribution of mean symmetry index and standard deviation values across speeds for the Soleus muscle in 12 participants after outlier removal.	37
Figure 13 Distribution of mean symmetry index and standard deviation values across speeds for the Vastus Lateralis muscle in 12 participants after outlier removal	37
Figure 14 Distribution of mean symmetry index and standard deviation values across speeds for the Biceps Femoris muscle in 12 participants after outlier removal.....	38

Figure 15 Comparative visualization of mean symmetry index and standard deviation before (25 participants) and after outlier removal (12 participants) for the Tibialis Anterior muscle across walking speeds	38
Figure 16 Comparative visualization of mean symmetry index and standard deviation before (25 participants) and after outlier removal (12 participants) for the Gastrocnemius Medialis muscle across walking speeds	39
Figure 17 Comparative visualization of mean symmetry index and standard deviation values before (25 participants) and after outlier removal (12 participants) for the Soleus muscle across walking speeds	39
Figure 18 Comparative visualization of mean symmetry index and standard deviation values before (25 participants) and after outlier removal (12 participants) for the Vastus Lateralis muscle across walking speeds	40
Figure 19 Comparative visualization of mean symmetry index and standard deviation values before (25 participants) and after outlier removal (12 participants) for the Biceps Femoris muscle across walking speeds	40
Figure 20 Percent changes in the symmetry index of lower limb muscles across different walking speeds – MAV feature analysis	43
Figure 21 Post hoc comparison results of Tibialis Anterior, Gastrocnemius Medialis, Soleus and Vastus Lateralis muscles (reference speed: 2.9 km/h) – MAV feature analysis	44
Figure 22 Post hoc comparison results of Tibialis Anterior, Gastrocnemius Medialis, Soleus and Vastus Lateralis muscles (reference speed: 3.2 km/h) – MAV feature analysis	45
Figure 23 . Post-hoc pairwise statistical significance matrix of symmetry index for Tibialis Anterior – MAV feature analysis	46
Figure 24 Post-hoc pairwise statistical significance matrix of symmetry index for Gastrocnemius Medialis – MAV feature analysis	47
Figure 25 Post-hoc pairwise statistical significance matrix of symmetry index for Vastus Lateralis – MAV feature analysis	49
Figure 26 Percent changes in the symmetry index of lower limb muscles across different walking speeds – AR feature analysis	51

Figure 27 Post-hoc comparison of Biceps Femoris muscle across walking speeds based on AR feature: Group 2.9 km/h shows statistically significant differences with groups 6.1, 6.5, 6.8, and 7.2 km/h ($p < 0.05$)	52
Figure 28 Post-hoc comparison of Biceps Femoris muscle across walking speeds based on AR feature: Group 3.2 km/h shows statistically significant differences with groups 4.7, 5.0, 5.4, 5.8, 6.1, 6.5, 6.8, and 7.2 km/h ($p < 0.05$)	53
Figure 29 Post-hoc pairwise statistical significance matrix of symmetry index for Biceps Femoris – AR feature analysis.	54
Figure 30 Percent changes in the symmetry index of lower limb muscles across different walking speeds – RMS feature analysis	57
Figure 31 Post-hoc comparison of Tibialis Anterior muscle across walking speeds based on RMS feature: Group 2.9 km/h shows statistically significant differences with groups 5.0, 5.4, 5.8, 6.1, 6.8, and 7.2 km/h ($p < 0.05$)	58
Figure 32 Post-hoc comparison of Tibialis Anterior muscle based on RMS feature: Group 3.2 km/h shows statistically significant differences with groups 5.0, 5.4, 5.8, 6.1, 6.8, and 7.2 km/h ($p < 0.05$)	58
Figure 33 Post-hoc comparison of Vastus Lateralis muscle based on RMS feature: Group 2.9 km/h shows a statistically significant difference with group 5.0, 5.4, 5.8, 6.1, 6.5, 6.8, and 7.2 km/h ($p < 0.05$)	59
Figure 34 Post-hoc comparison of Vastus Lateralis muscle based on RMS feature: Group 3.2 km/h shows a statistically significant difference with group 5.0, 6.1, 6.8, and 7.2 km/h ($p < 0.05$)	59
Figure 35 Post-hoc pairwise statistical significance matrix of symmetry index for Tibialis Anterior – RMS feature analysis	61
Figure 36 Post-hoc pairwise statistical significance matrix of symmetry index for Vastus Lateralis – RMS feature analysis	63
Figure 37 Frame-Based Symmetry Index Distribution in the Tibialis Anterior Muscle Across Walking Speeds	65
Figure 38 . Frame-Based Symmetry Index Distribution in the Gastrocnemius Medialis Muscle Across Walking Speeds	65

Figure 39 Frame-Based Symmetry Index Distribution in the Soleus Muscle Across Walking Speeds	66
Figure 40 Frame-Based Symmetry Index Distribution in the Vastus Lateralis Muscle Across Walking Speeds.....	66
Figure 41 Frame-Based Symmetry Index Distribution in the Biceps Femoris Muscle Across Walking Speeds.....	67
Figure 42 Post-hoc comparison of Gastrocnemius Medialis muscle in frame-based analysis: Nine walking speeds showed statistically significant difference from 2.9 km/h ($p < 0.05$)	68
Figure 43 Post-hoc comparison of Gastrocnemius Medialis muscle in frame-based analysis: Seven walking speeds showed a statistically significant difference from 3.2 km/h ($p < 0.05$)	68
Figure 44 Post-hoc pairwise statistical significance matrix of symmetry index for Gastrocnemius Medialis – Frame based analysis.....	70
Figure 45 Post-hoc comparison of Soleus muscle in frame-based analysis: Five walking speeds showed a statistically significant difference from 2.9 km/h ($p < 0.05$)	70
Figure 46 Post-hoc comparison of Soleus muscle in frame-based analysis: Five walking speeds showed a statistically significant difference from 3.2 km/h ($p < 0.05$)	71
Figure 47 Post-hoc pairwise statistical significance matrix of symmetry index for Soleus – Frame based analysis	72
Figure 48 Post-hoc comparison of Vastus Lateralis muscle in frame-based analysis: Ten walking speeds showed a statistically significant difference from 2.9 km/h ($p < 0.05$) ..	73
Figure 49 . Post-hoc comparison of Vastus Lateralis muscle in frame-based analysis: Nine walking speeds showed a statistically significant difference from 3.2 km/h ($p < 0.05$) ..	73
Figure 50 Post-hoc comparison of Vastus Lateralis muscle in frame-based analysis: Seven walking speeds showed a statistically significant difference from 3.6 km/h ($p < 0.05$) ..	74
Figure 51 Post-hoc comparison of Vastus Lateralis muscle in frame-based analysis: Six walking speeds showed a statistically significant difference from 4.0 km/h ($p < 0.05$) ..	74
Figure 52 Post-hoc pairwise statistical significance matrix of symmetry index for Vastus Lateralis – Frame based analysis.....	77

Figure 53 Correlation between walking speed and symmetry index based on MAV feature for each muscle.....	78
Figure 54 Correlation between walking speed and symmetry index based on AR feature for each muscle.....	79
Figure 55 Correlation between walking speed and symmetry index based on RMS feature for each muscle.....	80
Figure 56 Correlation between walking speed and symmetry index for each muscle for frame-based	81



LIST OF ABBREVIATIONS

sEMG	Surface Electromyography
SI	Symmetry Index
MAV	Mean Absolute Value
AR	Auto Regressive
RMS	Root Mean Square
TA	Tibialis Anterior
GM	Gastrocnemius Medialis
SOL	Soleus
VL	Vastus Lateralis
BF	Biceps Femoris
ANOVA	Analysis of Variance
SD	Standard Deviation
IQR	Interquartile Range
TM	Temporal Moment
VAR	Variance of EMG
ME	Mean Energy
VO	VOrder
EMAV	Enhanced Mean Absolute Value
SSI	Simple Square Integral
COV	Coefficient of Variation
EWL	Enhanced Wavelength
LDAMV	Log Difference Absolute Mean Value
MMAV2	Modified Mean Absolute Value 2
CI	Confidence Intervals
RF	Rectus Femoris

Chapter 1

Introduction

1.1 Background

Gait, one of the foundations of daily life activities, is to move the body in different directions at the desired speed. When we consider gait biomechanically, it is an important indicator that provides information about the individual's muscle coordination and balance abilities. The first thing considered in the analysis is the steps. A step refers to the time from one foot touching the ground to the other foot touching the ground (Kapri et al., 2021). Parameters such as the distance between the point of one heel touching the ground and the point of the same heel touching the ground, the distance between the point of one heel touching the ground and the point of the other heel touching the ground, the angle at which the feet touch the ground, step time, the time between the first contact of two successive steps of the same foot, the time the foot is in contact with the ground, the time the foot is in the air and not in contact with the ground, speed of the movement and the number of steps taken per minute are analyzed (Fukuchi et al., 2019; Roberts et al., 2017).

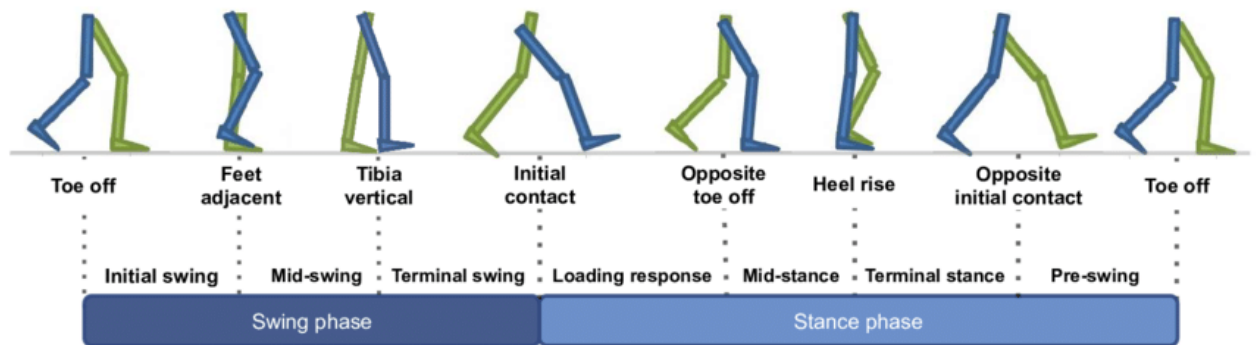


Figure 1. The Gait Cycle/Walk Cycle (Bergamini et al., 2024).

In general, these parameters play a crucial role in assessing an individual's movement dynamics and efficiency, and positive changes in these parameters increase the quality of life, increase the effectiveness of rehabilitation processes by increasing the functional capacities of patients, and positively affect their social participation (Leone et

al., 2018). When we consider all these, they play an important role in identifying possible abnormalities and underlying problems (Karataş et al., 2022).

In addition, gait analysis evaluations incorporate both kinematic (motion-related) and kinetic (force-related) analysis. While kinematic analysis records joint angles, linear and angular velocity, and acceleration are recorded in, kinetic analysis examines force components such as ground reaction and muscle forces. The data obtained from kinetic analysis allows the identification of forces acting on the moving body. In fact, these analyses help to identify musculoskeletal or neurological problems by identifying disorders that affect balance, coordination, and movement efficiency during walking (Broström et al., 2012).

Deviations from normal gait patterns, often referred to as gait abnormalities, can be caused by a variety of factors, including musculoskeletal and central nervous system disorders (Broström et al., 2012; Pradon et al., 2024) or muscle fatigue, biomechanical demands, and speed (Daunoraviciene et al., 2021; Iwańska et al., 2021). These deviations can negatively affect a person's gait balance and stability, causing them to expend more energy, and in the long term, can lead to musculoskeletal problems. These effects can reduce an individual's performance in daily life activities and overall quality of life. It is important to understand gait abnormalities to improve an individual's quality of life and determine strategies to regain balance.

In this context, whether the gait is symmetrical or not plays an important role in the assessment of an individual's movement mechanisms. Symmetry in gait patterns is an important factor in evaluating an individual's mobility, muscle coordination, and overall balance capacity. Specifically, gait symmetry analysis is utilized to evaluate the effectiveness of rehabilitation processes in individuals with musculoskeletal or central nervous system issues (Nasyuha et al., 2019).

In this study, we focus on the symmetry analysis of gait using electromyography (EMG) data collected from the left and right legs of subjects walking at different speeds, from the tibialis anterior, gastrocnemius medialis, soleus, vastus medialis and biceps femoris muscle groups, which are of great importance for controlling balance, pushing

and stability. EMG allows us to measure the muscle's response and electrical activity when a nerve stimulates the muscle, thus providing information about how the muscles behave throughout the gait cycle. For this purpose, the Symmetry Index (SI) method will be utilized. The 'Symmetry Index' (SI) method calculates symmetry as a percentage by comparing the muscle activation levels of both legs throughout the gait cycle, where a value of 0% indicates complete symmetry, while deviations from 0 indicate asymmetry (Daunoraviciene et al., 2021).

1.2 Statement of the Problem

The effects of different walking speeds on muscle activation and symmetry are not yet fully understood (Bergamini et al., 2024). Current literature emphasizes the importance of considering the effect of gait speed when assessing gait symmetry (Bergamini et al., 2024). In addition, it is stated in the literature that symmetry disorder is usually the result of the presence of pain in pathological gait or an underlying disorder (Cabral, 2018). The problem addressed in this study is to understand how speed affects gait symmetry and whether this effect varies among different muscle groups.

1.3 Purpose of the Study

This study aims to provide meaningful data on gait symmetry using EMG data obtained by focusing on five key muscle groups at different walking speeds. The findings will provide information on strategies for improving gait symmetry.

1.4 Hypotheses / Research Questions

This study addresses the following research questions and hypotheses:

- How did the symmetry between muscles change as speed changed?
- In which muscle groups were asymmetrically observed during speed changes?
- In which speed ranges were the most significant symmetrical differences observed?

1.5 Significance of Study

This research is looking at how much the difference between the left and right legs changes as walking speed increases. This is important because changes in symmetry can tell us a lot about balance, muscle control, or potential problems such as fatigue or injury. Seeing which speeds provide better symmetry could mean that walking becomes much more coordinated, which could be a sign of muscle balance or even force distribution.

1.6 Definitions

- **Gait:** Gait is the walking style of an individual at a certain speed that is related to musculoskeletal health.
- **Gait symmetry:** Gait symmetry is all about how similar or different the muscle activity of the left leg is compared to the right leg during walking.
- **EMG (Electromyography):** EMG is a method that measures the electrical activity in the muscle as a result of muscle stimulation.
- **Symmetry Index (SI):** A method that measures symmetrical differences between the left and right leg muscles.

Chapter 2

Literature Review

2.1 The Importance of Gait Symmetry and the Use of EMG

Gait symmetry is defined as harmony in the movements of the lower limbs while walking. It is related to how similar or different the muscle activity of the left leg is compared to the right leg. It is of great importance in terms of reducing energy expenditure, muscle fatigue and ensuring optimal balance (Roemmich et al., 2019). While temporal-spatial parameters and muscle activation patterns occur in a certain symmetry during walking in healthy individuals, this symmetry can be disrupted in pathological conditions (Doyle et al., 2022).

Gait symmetry can be observed especially in conditions such as stroke, Parkinson's disease, cerebral palsy or musculoskeletal disorders. Asymmetrical gait due to movement disorders can cause joint wear over time and increase the individual's risk of falling (Ataullah & De Jesus, 2024). Therefore, gait symmetry is a critical parameter for the diagnosis of pathological conditions and the evaluation of rehabilitation processes (Viteckova et al., 2018).

Electromyography (EMG) is an important technique that allows the measurement of muscle activation during walking. Using EMG signals, the activation patterns of specific muscle groups within the gait cycle can be analyzed and differences between the right and left sides can be determined. Understanding how muscle activation changes at different walking speeds an important way is to evaluate gait symmetry and enables the development of strategies to optimize the functional movements of individuals (Murray et al., 1984).

In this study, walking symmetry will be examined by comparing muscle activities between legs using EMG data containing muscle activity in both left and right legs for different speeds. It is aimed to compare different muscles by using symmetry index calculation for analysis to see how symmetry changes according to speed and which muscles show more or less symmetry. In this context, previous studies on the

biomechanical and neuromuscular basis of walking symmetry will be examined and the methods to be used in this thesis will be introduced.

2.2 Gait Symmetry: Current Research

Sadeghi et al. (1997) and Sadeghi et al. (2001) support the theory of functional walking asymmetry in healthy individuals, where there is a difference in support and propulsion functions due to different muscle strengths and associated mechanical energies, and this difference creates a natural asymmetry, while Sadeghi et al. (2000) also suggest that the functions of the two legs may be different from each other, with the dominant leg providing the propulsion and directing the movement, while the other performs the balance and support function, creating asymmetry even if there is no pathological condition.

Rice and Seeley (2010) showed that walking speed affects the balance of force between the dominant and non-dominant legs. In this study, the walking of 20 healthy individuals at nine different walking speeds was analyzed. When we look at the results, the support force of the dominant leg was found to be 2% more than the non-dominant leg at slow speeds. When the speed increased, the pushing force of the dominant leg was 12% more than the non-dominant leg. No significant functional asymmetry was observed at the preferred speeds. Considering all these, we see that the dominant leg also provides the support function, and the absence of asymmetry at preferred speeds shows us that symmetry occurs provided there is no pathological condition. As a result, functional asymmetry has been associated with walking speed. The most significant differences occur at fast and slow walking.

In a different study, walking symmetry was examined in 20 healthy individuals with slow, fast and preferred speed walking. While no significant mean difference was observed in slow and preferred speed, the dominant leg showed an increase in propulsive impulse in fast walking. No definitive hypothesis can be presented for the asymmetries observed during walking due to functional asymmetry (Seeley et al., 2008). In summary, one study related functional asymmetry to speed, while the other did not provide a

definitive hypothesis. Therefore, more research is needed on how speed changes affect not only the force distribution between the legs, but also walking dynamics such as balance, coordination and muscle activation patterns.

All these findings, when viewed from a biomechanical perspective, show that the dominant leg provides more propulsion, while the non-dominant leg provides more balance and support, resulting in a natural asymmetry. When viewed from a motor control perspective, it is understood that gait symmetry cannot be explained solely by muscle forces and mechanical energies, but how the central nervous system provides muscle activation, coordination and balance during gait is also a determining factor. In particular, how speed changes affect not only force distribution but also gait patterns, postural balance and muscle synchronization are important factors in the evaluation of gait symmetry.

Contrary to the above findings, in the study conducted by Plotnik et al. (2013) on the effect of three different walking speeds like preferred speed, slow and fast on asymmetry with 15 healthy individuals, it was reported that walking asymmetry was not affected by speed change, but the phase coordination index (PCI), a metric used to evaluate walking symmetry, was impaired in slow walking. These findings show that walking asymmetry should not be directly associated with speed change, but it has important effects in terms of coordination.

In studies conducted on unhealthy individuals, gait symmetry was examined together with speed. In the study by Prosser et al. (2022), when gait symmetry was examined in children with hemiplegia, who had a loss of movement on the right or left side of the body, it was observed that the symmetry was not affected by walking speed. This shows that speed may not be the main determining factor in gait symmetry not only in healthy individuals but also in individuals with motor loss.

Plotnik et al. (2013) and Prosser et al. (2022) reported that gait symmetry or asymmetry was not directly associated with speed change in their studies, but Rice and Seeley (2010) and Seeley et al. (2008) reported that speed changes were an important factor in the evaluation of gait symmetry.

Considering all these, there have been various studies in the literature on the use of Electromyography (EMG) to examine gait symmetry. Halim et al. (2019) focused on the fact that the assessment of gait asymmetry using EMG instead of traditional methods provides more information about muscle activation. In addition, it gives detailed information along with muscle activation like the functional roles of the muscles, more detailed examination of pathological gait analysis, use for the purpose of following progress in gait rehabilitation, and detailed information about balance problems by detecting muscle activation imbalance between the two legs. It was stated that more studies are needed in EMG-based asymmetry analysis.

Similarly, studies have been conducted to understand the effect of speed change on muscle activation and how muscles work during walking. In the study in which 35 healthy individuals participated, the activity of gastrocnemius medialis (GM), gluteus maximus (GMax), biceps femoris (BF) and rectus femoris (RF) muscles were measured using EMG at slow (1.32 ± 0.29 m/s), self-preferred speed (1.56 ± 0.36 m/s) and fast speeds (1.81 ± 0.43 m/s). As a result, it was found that speed change affected muscle activation, and the highest muscle activation was observed at the fastest and slowest walking speeds. In addition, muscle activation patterns differed at each speed. GMax was most activated at heel strike. GM showed the most activity during the propulsion phase. BF and RF were more activated at slow and fast speeds. In particular, RF and GM activity increased during fast walking, while GMax activity increased during slow walking to maintain balance (Sousa and Tavares, 2012). This finding reinforces the importance of using EMG in gait symmetry analysis by demonstrating the effect of walking speed on muscle activation mechanisms.

Hof et al. (2002) examined the effect of walking speed on muscle activation and analyzed how EMG profiles respond to speed changes. In this study, two groups of 20 healthy individuals were walked on a 10-meter walking track at five different speeds: 0.75 m/s, 1.00 m/s, 1.25 m/s, 1.50 m/s and 1.75 m/s, and EMG signals were collected from 14 different muscle groups; especially the activation of the Gastrocnemius Medialis (GM), Semitendinosus (ST), Tibialis Anterior (TA) and Rectus Femoris (RF) muscles was measured and step speeds and EMG data were analyzed. Muscle activation increased

regularly as walking speed increased. While the activation of some muscles remained independent of speed, an increase directly proportional to speed was observed in other muscles. For example: While the activation of the GM and ST muscles increased significantly as speed increased, a speed-independent activation pattern was observed in the TA muscle. As speed increases, GM activation increases especially in the propulsion phase. RF activity reaches its highest level in fast walking. TA activation peaks in the early phase of slow walking and in the late phase of fast walking. As a result, EMG profiles change depending on walking speed. While most muscles show higher activation as speed increases, some muscles work independently of speed. Changes in muscle activation depending on walking speed can be an important criterion for creating personalized exercise programs in rehabilitation processes.

Moreira et al. (2021) analyzes lower extremity kinematic, kinetic and EMG data of healthy individuals at controlled walking speeds and provides important data to understand muscle activation depending on walking speed. In this study, 16 healthy individuals were walked on a 10-meter walking surface at seven different speeds of 1.0, 1.5, 2.0, 2.5, 3.0, 3.5 and 4.0 km/h (0.28, 0.42, 0.56, 0.69, 0.83, 0.97, 1.1 m/s, respectively) and EMG signals were collected from the Tibialis Anterior (TA), Gastrocnemius Lateralis (GAL), Biceps Femoris (BF) and Vastus Lateralis (VL) muscle groups. As a result of the study, it was seen that muscle activation changed depending on walking speed. As in the study by Hof et al. (2002), muscle activation increased regularly as walking speed increased. EMG signals showed a linear increase with speed change in certain muscle groups. For example, the Gastrocnemius Lateralis (GAL) and Vastus Lateralis (VL) muscles were activated more as speed increased.

Franz et al. (2012) investigated how leg muscle activations change during flat, uphill and downhill walking and whether these changes depend on walking speed. EMG signals were collected from the Gluteus Maximus (GMAX), Biceps Femoris (BF), Rectus Femoris (RF), Vastus Medialis (VM), Medial Gastrocnemius (MG) and Soleus (SOL) muscle groups by walking 10 healthy young adults at three different speeds of 0.75 m/s, 1.25 m/s and 1.75 m/s. During flat walking (0° slope), muscle activation increases as walking speed increases. Especially in fast walking (1.75 m/s), ankle (MG, SOL) and knee

extensors (RF, VM) are activated more. Hip muscles (BF, GMAX) increase to provide more balance and stability during fast walking. In summary, the highest muscle activation is generally seen at the fastest walking speed. Neptune et al. (2008) and den Otter et al. (2004) showed in their studies that there is a linear relationship between walking speed and muscle activation, which supports the study of Franz et al. (2012).

Lythgo et al. (2010) investigated the gait symmetry of children and young adults at slow, free (normal) and fast walking speeds. 656 healthy children (5-13 years old) and 81 young adults (18-27 years old) walked on a flat track of 4.3 m and 4.9 m length at three different speeds. The basic parameters used in determining asymmetry, such as step time (Step Time), stride length (Single Support Time), double support time (Double Support Time), were examined according to speeds. Stride length increased as speed increased, but its duration and double support time decreased. These results show that gait symmetry can change with speed.

In the study in which 120 healthy individuals participated, kinetic values of the left and right lower extremities were recorded to evaluate gait asymmetry. The symmetry index value was determined by these values. It was concluded that 0% was very good symmetry, 2.1% - 5.0% was good symmetry, 5.1% - 9.4% was poor symmetry and 9.5% and above was very poor symmetry. It has been suggested that these symmetrical values stated in healthy individuals can be used as a reference in many areas such as gait asymmetry for rehabilitation and clinical studies, and for the diagnosis of gait disorders (Kaczmarczyk et al., 2017).

General Evaluation

Functional asymmetry, the relationship between walking speed and functional asymmetry, is seen in studies on the effect of walking symmetry analysis of muscle activations that change with speed. While some studies support the existence and neurophysiological basis of functional asymmetry (Sadeghi et al., 2000, Sadeghi et al., 2001), others have studied the effect of walking speed on force distribution between dominant and non-dominant legs (Rice & Seeley, 2010, Seeley et al., 2008). On the other hand, Plotnik et al. (2013) and Prosser et al. (2022) evaluated the effects of speed on symmetry and coordination, Halim et al. (2019) emphasized the importance of EMG-based studies in walking symmetry, Sousa & Tavares (2012) reported differences in muscle activation with EMG-based studies; Hof et al. (2002), Moreira et al. (2021), Franz et al. (2012), Neptune et al. (2008) and den Otter et al. (2004) demonstrated the linear relationship between speed increase and muscle activation. In addition, Lythgo et al. (2010) examined the changes in spatio-temporal parameters according to speed and the change in gait symmetry with speed, while Kaczmarczyk et al. (2017) emphasized the importance of evaluation based on symmetry index in clinical practice.

To better understand whether gait asymmetry really exists in healthy individuals and its underlying causes, this study aims to see how much the difference between the left and right legs changes as walking speed increases. This is important because changes in symmetry can tell us a lot about balance, muscle control, or possible problems such as fatigue or injury. For example, if asymmetry increases at faster speeds, this could mean that walking becomes less coordinated, which could be a sign of muscle imbalances or unequal force distribution. As a result, it appears that gait asymmetry is not only related to biomechanical factors but also to neuromuscular control due to speed changes. EMG data should combine these two approaches to examine in more detail the effects of speed changes not only on force distribution but also on muscle activation patterns.

2.3 Targeted Muscles and Their Functions

2.3.1 Tibialis anterior. The TA is the largest of the four muscles in the anterior leg and is the main muscle group located in the anterior compartment of the lower leg. It has a large muscle fiber originating from the lateral tibia (outer part of the knee bone). The tibialis anterior tendon (TAT) is found on the distal part of the tibialis anterior muscle. The TAT originates from the distal tibia, runs through the anterior ankle and dorsum of the foot, and inserts into the medial cuneiform and the base of the first metatarsal. The TA is responsible for dorsiflexion and inversion of the foot. It also helps to keep the foot balanced and stable (Juneja & Hubbard, 2023).

2.3.2 Gastrocnemius medialis. The gastrocnemius muscle, located on the back of the leg, is a combination of muscle fibers that play a role in performing and stabilizing the movements of the legs and in activating the joints. It has two heads, medial and lateral. The medial head (caput mediale) starts from the back-upside of the condyle medialis of the femur and the back surface of the femur. The gastrocnemius muscle, a strong muscle, can control the back of the leg. It has fiber structures that can contract very quickly. It has basic functions such as allowing people to walk, run, and stand on their toes (Bordoni & Varacallo, 2023).

2.3.3 Soleus. The soleus muscle is in the lower leg. It extends from the tibia and fibula bones to the Achilles tendon. The soleus muscle, which has a slow-twitch fiber structure, allows for movements such as walking and running, which are frequently performed daily (Balius et al., 2012).

2.3.4 Biceps femoris. The biceps femoris muscle is a muscle structure belonging to the Hamstring muscles located in the upper back of the human legs. This muscle is known for its two-headed structure, the long head and the short head. The long head makes up the larger part of the muscle and helps stretch the hip. The short head contributes to flexion of the knee. The harmonious operation of these two sections ensures that our legs are both strong and flexible. Thus, more effective performance is achieved in daily movements and sports activities. Especially in sports fields where activities such as jumping, hopping and leaping are required, this muscle ensures that the relevant movements are performed. It helps with flexion in the knee joint and external rotation movement of the knee. Strengthening this muscle correctly protects general leg health, increases performance and reduces the risk of injury (Rodgers & Raja, 2023).

2.3.5 Vastus lateralis. The vastus lateralis muscle is in the quadriceps muscle group. The vastus lateralis muscle, which provides 40% of the total strength of the quadriceps, is the largest muscle structure in the muscle group it belongs to. The vastus lateralis muscle, located in the leg, is very important for people's knee extension movements. It allows people to go up and down stairs, ride a bike, and perform movements that require flexing their knees (Biondi & Varacallo, 2023).

2.4 Walking Phases

2.4.1 Stance phase. The stance phase, which makes up 60% of the entire walking cycle, is the phase where the foot touches the ground and supports body weight. During stance phase, specific muscle groups are actively involved in supporting body weight and propulsion.

Hip extensors (gluteus maximus and hamstrings) stabilize the hip and propel the body forward. Knee extensors (quadriceps) provide control of the knee and support body weight. Ankle plantar flexors (gastrocnemius and soleus) stabilize the ankle and provide propulsion (Abu-Faraj et al., 2015). The stance phase consists of three subcomponents: double support, single support and pre-swing. The muscles that are more activated in this

phase are Biceps Femoris (BF), Medial Gastrocnemius (MG) and Rectus Femoris (RF). Muscle activation varies according to the components of the stance phase.

For example, in the double support phase, the activation of the RF, Semitendinosus (SE), and Lateral Gastrocnemius (LG) muscles is clearer. Although the SE and LG muscles are muscles that play an active role in the swing phase, their activation is seen in the stance phase. The reason for this is that even if you are in the stance phase in the double support phase, some muscles can be activated when one leg is preparing for swing (Daunoraviciene et al., 2021). While BF and MG are active in the single support phase, in the mid-stance phase, which is a sub-phase of the single support phase, the Tibialis Anterior and Soleus muscles are significantly activated, according to the study by Schmitz et al. (2009). In the pre-swing phase, it was determined that the BF and RF muscles showed high activation. When the symmetry analysis was performed according to the phases of the gait cycle, significant differences were seen in the BF and MG muscles in the stance phase, but this asymmetry indicates that the muscles are active at different times to maintain balance during normal walking and provides stabilization (Daunoraviciene et al., 2021).

In the study of Sousa and Tavares (2012), the effects of different walking speeds on the activation of the Gastrocnemius Medialis (GM), Gluteus maximus (GMax), BF and RF muscles and on the stance phase are examined. It is observed that GMax and BF show the highest activity during the stance phase. In the study of Moreira et al. (2021), it is observed that as the walking speed increases, the ankle dorsiflexion torque, knee flexion torque and hip extension torque increase, which helps stability and body propulsion.

2.4.2 Swing phase. The swing phase, which comes after the stance phase and constitutes 40% of the entire gait cycle, is the phase in which the foot lifts off the ground and moves forward for the next step.

The muscles that play an active role in the swing phase are the hip flexors (iliopsoas and rectus femoris), knee flexors (hamstrings), and ankle dorsiflexors (tibialis anterior) (Abu-Faraj et al., 2015). The Lateral Gastrocnemius (LG) and Semitendinosus (SE) muscles

play an important role in this phase. When the right and left leg muscle activations are compared, asymmetry is evident in the LG muscle in the swing phase (Daunoraviciene et al., 2021).

Moreira et al. (2021) observe that with increasing walking speed, there is an increase in ankle dorsiflexion torque, knee flexion torque, and hip extension torque. These changes help to create a faster and more balanced step cycle depending on walking speed. Especially in fast walking, proper adjustment of these torques reduces the risk of falls, increases energy efficiency, and controls the forward motion of the leg.

Producing more torque in both phases as walking speed increases, is necessary to maintain the balance of the legs, body and ensure a balanced gait. Therefore, ankle dorsiflexion torque, knee flexion torque and hip extension torque are important in both stance and swing phases. In addition, in the process of symmetry analysis according to muscle activation, when the activation of the right and left legs was compared, it was observed that the left leg was more active early on, but balance was achieved with the right side over time. As a result, when the muscle activations in the swing and support phases of the gait cycle were examined, more pronounced muscle asymmetries were seen in the support phase compared to the swing phase (Daunoraviciene et al., 2021). With this information, we saw which muscles were more active in which phase and their effects on walking symmetry analysis.

2.5 Gait Symmetry Analysis Using EMG Data

The symmetry index is a formula used to measure and compare gait symmetry numerically. This formula is applied using the values measured on the left and right lower extremities and shows whether there is a difference and, if so, the percentage. While 0% indicates full symmetry, moving away from this value indicates asymmetry, but some studies have shown that full symmetry cannot be achieved. In addition, gait symmetry depends not only on gait speed but also on the method used for measurement (where on the body the data is taken from and which mathematical analysis is performed) (Bergamini et al., 2024).

Four different methods were compared for calculating gait symmetry. These methods are Ratio Index (RI), Symmetry Index (SI), Gait Asymmetry (GA) and Symmetry Angle (SA). RI is an index based on the ratio of right and left leg values. SI is an index that normalizes the right and left side differences, also interpreted as “% difference”. GA is the logarithmic transformation of RI. Finally, SA is an index that measures the vector angle between the right and left leg values. Measurements were made on 58 healthy individuals, and the measured parameters were step length, step duration, stance phase, load response, single support duration, pre-swing and swing phase. According to the results of the study, SI was determined as the most sensitive index in evaluating gait symmetry. It is recommended to use SI to evaluate gait symmetry in clinical rehabilitation processes. It is also recommended to use SI as a standard measurement (Błażkiewicz et al., 2014).

- Ratio Index (RI)

$$RI = 1 - \frac{X_R}{X_L} \times 100\% \quad (1)$$

where x_R is the value of right limbs, x_L is the value of left limbs.

- Symmetry Index (SI)

$$SI = \frac{|X_L - X_R|}{0.5 \cdot (X_L + X_R)} \times 100\% \quad (2)$$

- Gait Asymmetry (GA)

$$GA = \ln \left(\frac{X_R}{X_L} \right) \times 100\% \quad (3)$$

- Symmetry Angle (SA)

$$SA = \frac{45^\circ - \arctan \left(\frac{X_R}{X_L} \right)}{90^\circ} \times 100\% \quad (4)$$

In another study examining 31 articles, since there is no standard approach to measuring walking symmetry, it examines these measurements by dividing them into

groups. It divides walking symmetrical measurements into four main groups. One of these is Discrete Approaches, which includes formulas such as “Ratio Index, Symmetry Index (Robinson Index) and Symmetry Angle”. Symmetry Index stands out as common and reliable in the literature thanks to its simple formula, but it also states that normalization is required for the interpretation of its results (Viteckova et al., 2018).

2.6 Effect of Speed on Gait Symmetry

We will examine the place of speed, one of the factors affecting walking symmetry, in the literature, about its effect on symmetry. In the examination of the factors affecting walking symmetry, it is stated that the lower extremities do not move completely symmetrically during walking and a more pronounced asymmetry occurs with pathological disorders. In the study where 60 scientific articles were examined, it was concluded that there is a certain degree of natural asymmetry even in a normal walk. Walking symmetry was examined at nine different speeds in the study. It was investigated how the change in speed affected walking asymmetry and it was stated that increasing the speed positively affected walking symmetry, but in certain pathological conditions (e.g. paralysis or prosthesis use), increasing the speed caused the asymmetry to worsen. It was observed that walking asymmetry was more pronounced at low speeds and individuals consciously used more asymmetric strategies to maintain balance (Nasirzade et al., 2017).

While Goble et al. (2003) suggested that speed improves symmetry, Plotnik et al. (2013) could not find a significant relationship between them. Lythgo et al. (2010) found that increasing or decreasing walking speed did not affect symmetry in the study of gait symmetry measures in children and young adults at different walking speeds, and that even the symmetry differences in step and stance duration remained very low. It was stated that healthy children's walking is symmetrical and will not be largely affected even if the speed changes. Perttunen et al. (2004) stated that walking asymmetry increases as speed increases, and Patterson et al. (2008) suggested that increasing walking speed decreases symmetry in paralyzed individuals. Along with all these studies, Patterson et al. (2009) mentioned an inverse relationship between symmetry ratio and walking speed, like the

study by Nasirzade et al. (2017). It was observed that symmetry disorder was more pronounced in individuals walking slower.

When we look at these studies, we can say that it would be incomplete to evaluate walking symmetry without commenting on the speed factor.

2.7 Rationale For Methodological Selection

Bergamini et al. (2024) investigated the speed and index dependence of walking symmetry at seven different speeds, 0.28, 0.56, 0.83, 1.11, 1.39, 1.67 and 1.95 m/s, and observed changes in symmetry values at certain speeds. When evaluated according to speed, it is seen that walking symmetry is quite variable at low speeds, i.e. less stable. This shows that the gait is asymmetric. At medium speeds (1.11 - 1.39 m/s), symmetry values reach the highest level and are evaluated as the most optimized speed ranges. At high speeds, no further stabilization is provided in symmetry, it remains constant. In line with all this information, it shows that symmetry becomes stable with the increase in walking speed and the most ideal symmetry range is 1.11 - 1.39 m/s.

In the study conducted by Nasirzade et al. (2017), nine different speeds of 0.5 m/s, 0.7 m/s, 0.9 m/s, 1.1 m/s, 1.3 m/s, 1.5 m/s, 1.7 m/s, 1.9 m/s and 2.1 m/s were examined and their effects on gait asymmetry were evaluated. No direct classification was made for the slow, normal and fast gait intervals of the speeds, but if we were to list the speeds from smallest to largest, it was stated that the first speeds were slow, the middle speeds were normal and the last speeds were fast. When evaluated according to this information, more asymmetry was observed at slow speeds (0.5 - 0.9 m/s), while better symmetry was observed at high speeds (1.7 - 2.1 m/s).

Considering which biomechanical function of the muscles is more important during normal walking, it is emphasized that the Soleus muscle is responsible for pushing the trunk forward, while the gastrocnemius muscle is important for initiating the swing phase (Schmitz et al., 2009). Joint control mechanisms are controlled by muscles, like knee extension is provided by the knee extensor muscles and plantar flexion is provided

by the plantar flexors. When we look at the knee joint extensors, it consists of the quadriceps group. In addition, the triceps surae (gastrocnemius and soleus), which are in the main muscle group in plantar flexion, contribute to knee extension. The hamstring muscle group also plays a role in knee flexion and knee stabilization. Foot dorsiflexion and stabilization also play a fundamental role during walking (Brunner & Rutz, 2013).

Murray et al. (1984), who examined muscle activations with walking speed, observed that as walking speed increased, activation of the gluteus maximus, hamstrings, quadriceps and calf muscles increased, but remained at a low level at low speed.

The symmetry index analysis performed using EMG data at different walking speeds is also evaluated on the features extracted from EMG data. In the studies conducted, there are 3 different feature groups. These are time domain, frequency domain and time-frequency domain. Time domain calculation is the most common way to extract features from EMG signals due to its simplicity, fast computation, being more suitable for short-term signals, low sensitivity to environmental noise and easy applicability, and is widely used in studies on human movements. Time is directly taken as an independent variable and calculated (Sun et al., 2022, Cao et al., 2018).

When domain studies are examined, Phinyomark et al. (2012) grouped the features to understand whether the EMG features are repetitive or not and stated that most of the time domain features repeat each other because they have similar mathematical structures and show similar distributions. In future studies, it is emphasized that it is important to select independent and non-similar ones instead of increasing the number of features.

How symmetry changes at which walking speeds, the basic biomechanical function of muscles during normal walking, and muscle activation patterns are investigated in the literature by Bergamini et al. (2024), Nasirzade et al. (2017), Schmitz et al. (2009), Brunner & Rutz (2013) and Murray et al. (1984). On the other hand, it emphasizes the importance of the reasons why which domain feature is widely preferred when performing symmetry analysis with the feature extraction method using EMG signals at different speeds (Sun et al., 2022, Cao et al., 2018) and what should be considered when selecting features (Phinyomark et al., 2012).

Chapter 3

Methodology

3.1 Study Design And Participants

The experiments were conducted in the Biomechanics Laboratory of Bahçeşehir University Biomedical Engineering Department. A total of 25 healthy participants were included in the study. The participation criteria for the participants are as follows.

- Providing informed consent
- No history of lower extremity injury
- No neurological disorders affecting motor control, balance or muscle function
- Agreeing to have all necessary measurements taken for the study

Participants were selected according to these criteria and were informed in detail about the objectives and procedures of the study.

3.2 Instruments And Devices

3.2.1 EMG. Trigno® Wireless Biofeedback (SN: SP-W02C-1357) System was used to capture the EMG activity. Three main parts make up the EMG equipment utilized in the study: a base station, sensors, and software. The base station is in charge of gathering data from the sensors and acts as the system's central hub with a sampling frequency of 2148Hz. The program is utilized for both EMG data analysis and system control. (Halabi et al., 2019)

The device, which allows for seamless recording of biomechanical signals, also provides data management via Delsys' proprietary EMGworks Acquisition software. The Trigno system's ability to provide accurate and reliable surface EMG (sEMG) data is enhanced by the integration of noise-resistant wearable sensors and "parallel-bar" technology (De Luca et al., 2011).



Figure 2. Delsys Trigno wireless EMG system (Halabi et al., 2019).

3.2.2 XSENS. The Kinematics of Joint Angles measurement was performed using the XSENS Awinda system (XSENS Technologies B.V., Enschede, The Netherlands). Xsens Awinda is a motion capture system with 17 wireless sensors (IMU – Inertial Measurement Unit) worn on the body with adjustable straps and a sampling frequency of 60 Hz. It is connected to the computer via a Wi-Fi router. The sensors (IMU – Inertial Measurement Unit) are placed at specific points on the body and collect movement data (Schepers et al., 2018).

MVN analyzes use IMU data to create a biomechanical model. The biomechanical model created to accurately track the subject's movement consists of a total of 23 segments, including the main segments like pelvis, spine (L5, L3, T12, T8), neck, head, shoulders, upper arms, forearms, hands, upper legs, lower legs, feet, and toes. Each joint movement in the model is represented by 3D angles (Schepers et al., 2018).



Figure 3. Xsens sensor plugged into Awinda station (MTw Awinda User Manual, 2018).

To ensure temporal synchronization of the motion capture system (XSENS Awinda) and EMG measurements, an additional device called the Delsys Trigger Module was used, which acts as a bridge between the systems. This module receives the trigger signal from the XSENS base station and transmits it to the EMG base station, thus starting data collection on both systems simultaneously.



Figure 4. Delsys trigger module (Delsys Incorporated, n.d.).

3.3 Data Acquisition

3.3.1 EMG. Before obtaining the data, preliminary preparations were made for the measurement. The muscle areas where the EMG data would be obtained were determined and the relevant area was cleaned with alcohol and had their hair removed to obtain a good signal quality. sEMG electrodes were placed on the biceps femoris, vastus lateralis, gastrocnemius medialis, soleus and tibialis anterior muscles according to the SENIAM recommendations, which are the standards for surface electromyography (Stegeman & Hermens, 2007). After placement, the sensors were tightly fixed with adhesive tape to ensure stability and minimize movement-related distortions during data collection.

3.3.2 XSENS. To analyze the spatio-temporal parameters of gait, sensors were placed on the participants. Since it is important to attach the sensors correctly, the XSENS MVN user manual was used as a basis for placement (Xsens Technologies B.V., 2021). The sensors were fixed using Xsens strapping bands and the participants were equipped with the XSENS Awinda system. Since an avatar of the participants would be created, measurements of their body segments were taken. First, a calibration was performed. After the participants held a fixed upright N-pose for three seconds, they walked forward and back to the starting point, completing their calibration. If an unsuccessful calibration occurred, the same process was repeated until a successful calibration was achieved.

3.4 Experimental Protocol

The subjects walked at 13 different speeds, measured in km/h. Here are the speeds they performed: 2.9, 3.2, 3.6, 4.0, 4.3, 4.7, 5.0, 5.4, 5.8, 6.1, 6.5, 6.8, and 7.2 km/h. For each speed, the subjects completed 50 gait cycles, which is one full movement cycle of walking (from the right foot striking the ground to the next time the right foot strikes the ground). Heel strikes (the point where the heel touches the ground) were used to divide the data into cycles. Right heel strikes were used to identify the start of the gait cycle for the right leg, left heel strikes were used to identify the gait cycles for the left leg. Thus, for

each subject, for each speed, 50 gait cycles of data were obtained for both the left and right legs.

3.5 Data Analysis

To analyze EMG data in this study, pre-processing steps were applied to the EMG raw data to ensure that it was clean and usable. These steps are Detrending, Filtering, Rectification, and Smoothing. Notch Filter was applied to cut 50 Hz noise components originating from the city network. When recording EMG, very low and very high frequencies are generally not very meaningful for muscle activity. A fourth-order Butterworth band pass filter with a lower cutoff frequency of 20 Hz and a higher cutoff frequency of 450 Hz was used to remove or attenuate the non-meaningful frequency (Valentinuzzi, 2007). In many biomedical recordings, such as an EMG, the signal may drift up/down over time due to interaction between the electrodes and the skin, breathing (respiration) movement, body temperature changes, or shifts in the device (Chowdhury et al., 2013). This unwanted, low-frequency component makes analysis difficult. The detrending method was applied to clean the slowly changing (trend) part and make the parts of the signal that are wanted to be examined (usually mid-high frequency components) clearer. Thus, all shifts in the signal were eliminated to focus on real muscle activity. In the raw data where the muscle activity signal oscillates positively and negatively, the absolute value of the negative values was taken, and Rectification was applied to convert all negative parts in the signal to positive. Finally, sharp, unnecessary protrusions in the data were removed with Smoothing.

Synchronized datasets were obtained by resampling to harmonize the different sample frequencies obtained from EMG and Xsens. After the data was cleaned and synchronized, it was segmented using heel strikes to look at each gait cycle separately. After cleaning and synchronizing the data, segmented using heel strikes to look at each gait cycle individually.

3.5.1 Feature extraction from emg data. For each muscle, extracted 14 EMG features from the raw EMG data after it was pre-processed (detrended, filtered, rectified, and smoothed). These features are based on time components represent different characteristics of muscle activity. These features include MAV (Mean Absolute Value), RMS (Root Mean Square), TM (Temporal Moment), VAR (Variance of EMG), SD (Standard Deviation), ME (Mean Energy), VO (VOrder), EMAV (Enhanced Mean Absolute Value), SSI (Simple Square Integral), AR (Auto Regressive Model), COV (Coefficient of Variation), EWL (Enhanced Wave Length), LDAMV (Log Difference Absolute Mean Value), and MMAV2 (Modified Mean Absolute Value 2).

3.5.2 Features selection. Based on the studies of Phinyomark et al. (2012) in the literature, the most frequently used features among these 14 features extracted based on time domain are MAV, RMS, VAR, SD, TM, SSI, VO, AR, MMAV2, and among these, VAR, SD, SSI, VO, MMAV2 were not preferred because they carry similar information with MAV, and TM3 was not preferred because it was not close to zero in some movements and its discrimination was weak compared to other features. Considering that the results evaluated according to only two features may be different from each other, RMS was preferred as the third feature despite having similar features with MAV to make sense of the results.

The feature-based time features extracted from EMG data, which we also consider in symmetry index evaluation, and which do not have a similar mathematical structure and are independent of each other, can be listed as follows.

- Mean Absolute Value (MAV)

It is the average of the absolute values of all samples of the EMG signal. It indicates the overall intensity of muscle activation (Phinyomark et al., 2012).

$$MAV = \frac{1}{N} \sum_{i=1}^N |x_i| \quad (5)$$

where x_i is the *i-th* sample of the EMG signal and N is the total number of samples.

- Auto Regressive Model (AR)

The AR model is used to make the current value of a signal more meaningful and measurable because the EMG signal is a noisy and complex signal, and these signals change as the muscles move. The AR is a model that estimates the current value of a signal by looking at several previous values of that signal. Since it is a mixture of past values, a small margin of error is also added (Phinyomark et al., 2012).

$$x_i = \sum_{p=1}^P a_p x_{i-p} + w_i \quad (6)$$

where x_i is the current EMG signal sample, a_p represents the ***p*-th** autoregressive coefficient, P is the order of the model (which is set to 4 in our study), and w_i is the white noise error term.

- Root Mean Square (RMS)

RMS is a commonly used feature in EMG signal analysis. This feature is related to muscle contraction force and non-fatiguing muscle contractions. It is also similar to the standard deviation method (Phinyomark et al., 2012).

$$RMS = \sqrt{\left[\left(\frac{1}{N} \right) \sum_{i=1}^N x_i^2 \right]} \quad (7)$$

where x_i is each sample of the signal, and N is the number of samples.

In the study, we will see the results of the symmetry index analysis performed by examining the EMG data from which MAV, AR and RMS features were extracted in the results section.

3.6 Outlier Detection

In this study, symmetry indices were calculated using EMG data collected from 25 subjects at different walking speeds. However, after visualizing the obtained values, it was

observed that some participants' data showed significant deviations from the general distribution. Since these deviations could statistically mislead the analysis results, outlier detection was applied to increase the reliability of the analysis.

The quartile method was preferred to determine outliers. The `isoutlier` (... , 'quartiles') function used in the MATLAB environment examined the symmetry indices for each speed level and accepted the values outside the limits according to the interquartile range (IQR) method as potential outliers.

According to this method:

- Q1: The first quarter value representing the lower 25% of the data.
- Q3: The third quarter value representing the upper 75% of the data.
- IQR (Interquartile Range): Calculated as $Q3 - Q1$.

A data point is considered an outlier if it is less than $Q1 - 1.5 \times IQR$ or greater than $Q3 + 1.5 \times IQR$.

With this approach, while the natural variation in the data is preserved, the effect of extreme values that could statistically mislead the analysis results is reduced. The detected outlier subjects are excluded from the analysis. The `isoutlier` (... , 'quartiles') function we use in MATLAB automatically manages this mathematics in the background.

3.7 Data Structure

To provide different perspectives in the analysis of walking symmetry, the analysis will be performed separately on the feature matrix and percentile matrix, allowing detailed comparisons to be made for speed.

Since each matrix contains muscle activity data for different walking speeds, how the matrix structures are organized is important for the analysis.

3.7.1 Feature matrix (Size: 16,250 x 71). This matrix stores the features extracted from EMG data.

- Rows (16,250): The matrix is organized first by subject and then by speed. Each subject has 650 rows, divided into 50 gait cycles per speed for each of the 13 speeds.
- Columns (71):
 - The first column contains the speed labels (e.g., 2.9, 3.2, 3.6, etc.)
 - The remaining 70 columns contain the EMG features for the five muscles, structured as:
 - Columns 2-15: Features for Tibialis Anterior
 - Columns 16-29: Features for Gastrocnemius Medialis
 - Columns 30-43: Features for Soleus
 - Columns 44-57: Features for Vastus Lateralis
 - Columns 58-71: Features for Biceps Femoris
- For each muscle, 14 features were extracted in order. Starting with the Tibialis Anterior muscle, this order is the same for all muscles. The order of the features is as follows:
 - Column 2: MAV, Column 3: RMS, Column 4: TM, Column 5: VAR, Column 6: SD, Column 7: ME, Column 8: VO, Column 9: EMAN, Column 10: SSI, Column 11: AR, Column 12: COV, Column 13: EWL, Column 14: LDAMV, Column 15: MMAV2

3.7.2 Percentile matrix (Size: 16,250 x 501). This matrix contains raw muscle data (EMG preprocessed signals).

- Rows (16,250): The same structure as the feature matrix. Each subject has 650 rows, and these are further divided into 50 gait cycles per speed for each of the 13 speeds.
- Columns (501):
 - The first column contains the speed labels (e.g., 2.9, 3.2, 3.6, etc.).
 - The remaining 500 columns are the EMG data for the five muscles, each muscle occupying 100 columns:
 - Columns 2-101: Tibialis Anterior EMG data
 - Columns 102-201: Gastrocnemius Medialis EMG data
 - Columns 202-301: Soleus EMG data
 - Columns 302-401: Vastus Lateralis EMG data
 - Columns 402-501: Biceps Femoris EMG data

3.8 Analyzing Symmetry Using EMG Data

In this study, the Symmetry Index method, which is frequently used in literature and has validity in clinical applications, was preferred for symmetry analysis.

EMG data collected at different speeds include left and right leg muscle activities. These data were normalized at the time series (frame-based) and feature-based levels before calculating the symmetry index. In both methods, 50 gait cycles of each subject at each speed were evaluated separately for the relevant muscles. At the time series level, scaling was applied according to the maximum value of each muscle at each time point; at the feature level, scaling was applied according to the maximum value of each feature in its own column. The normalized data obtained were used in the symmetry index calculations.

The Symmetry Index (SI) formula was used to measure symmetry. The formula will compare each muscle on the left and right legs at each speed to see if there's a difference. This gives a percentage value, with 0% meaning perfect symmetry (left leg equals right leg) and any percentage higher than 0 meaning more asymmetry.

The formula used:

$$SI = \left(\frac{EMG_{\{right\}} - EMG_{\{left\}}}{EMG_{\{right\}} + EMG_{\{left\}}/2} \right) \times 100 \quad (8)$$

where $EMG_{\{right\}}$ is the muscle activity of the right leg, $EMG_{\{left\}}$ is the muscle activity of the left leg.

This was used for each muscle (tibialis anterior, gastrocnemius, etc.) and for each of the 13 walking speeds. This analysis was applied to two different types of data, each organized in its own matrix.

3.8.1 Calculate symmetry for the feature matrix. The symmetry index was calculated using the values created using the MAV, AR and RMS feature for a total of 12 participants, 13 different speeds, and for each of the five lower extremity muscles, namely Tibialis Anterior, Gastrocnemius Medialis, Soleus, Vastus Lateralis, and Biceps Femoris. The symmetry index of each subject at each speed in the relevant feature of each muscle was calculated separately. Then, the average of the symmetry indexes of all subjects at the relevant speed for each muscle was calculated to calculate the average symmetry index at that speed. In addition, the standard deviation (SD) was calculated to show how differently that muscle works among individuals.

3.8.2 Calculate symmetry for the percentile matrix. For each muscle, the walking process was divided into 100-time frames and these frames were structured as columns in the data matrix. The symmetry index was calculated separately for each frame. In this calculation, the EMG data of the left and right extremities were applied to the symmetry formula at each time point (frame) to obtain symmetry indices on a frame basis.

For each walking speed, 100-frame symmetry index data were calculated separately for each of the 12 subjects. The symmetry indices of the same numbered frames were combined by averaging over the 12 subjects and a single average value was created for each frame. Then, a general average was taken from these 100-frame average values and the average symmetry index of the relevant muscle for that walking speed was calculated. This process was applied separately for a total of 13 different walking speeds ranging from 2.9 km/h to 7.2 km/h.

The average symmetry indices obtained for each speed level and their standard deviation (SD) values are presented in table and graphic format.

3.9 Statistics

To see statistical differences for each muscle at different speeds over features or frames, first, whether there was a statistically significant difference in the muscles was analyzed with ANOVA. Then, in the muscle groups where there was a significant difference, Tukey-Kramer post-hoc tests were used to evaluate the statistical significance between the speed groups.

In the post hoc analysis, 95% confidence intervals of the differences between the groups were calculated. The LowerCI and UpperCI columns show the lower and upper limits of these confidence intervals (CI). Comparisons that do not include zero confidence interval indicate statistically significant differences.

3.10 Speed - Symmetry Index Correlation Analysis

To evaluate the relationship between speed and SI, the pearson correlation coefficient (r) and the relevant p value to determine the significance of the correlation coefficient were calculated in MATLAB.

The limits suggested by Dancey and Reidy (2007) were considered in the interpretation of the coefficients obtained. When the correlation coefficient (r) was between 0.0 and 0.1, the strength of the relationship was considered negligible, between 0.1 and 0.3, weak, between 0.4 and 0.6, moderate, between 0.7 and 0.9, strong, and between 0.9 and 1.0, very strong. The correlation coefficient (r) and significance level (p) values obtained as a result of the analysis are detailed in the "Results" section.



Chapter 4

Results

4.1 Outlier Removal

When the data of 25 subjects regarding symmetry indices were analyzed, the measurements of 13 subjects were determined as outliers at certain speed levels and were excluded from the analysis. After this process, the data set was rearranged with 12 participants.

Below, Figures 5–9 present the symmetry index distributions obtained from 25 participants; Figures 10–14 show the distributions recalculated with the data of 12 subjects after the removal of outlier subjects. In Figures 15–19, both cases are presented comparatively.

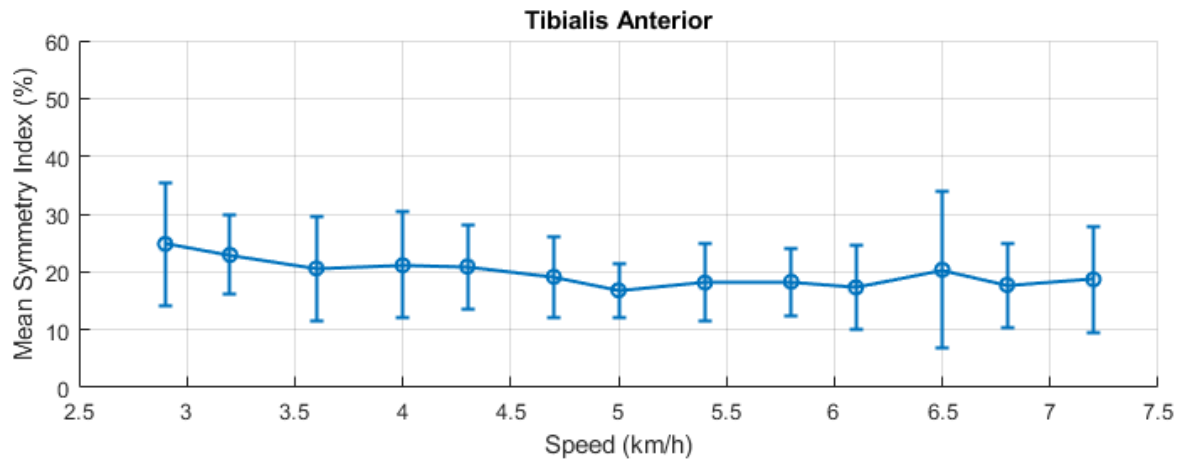


Figure 5. Distribution of mean symmetry index and standard deviation values across speeds for the Tibialis Anterior muscle in 25 participants.

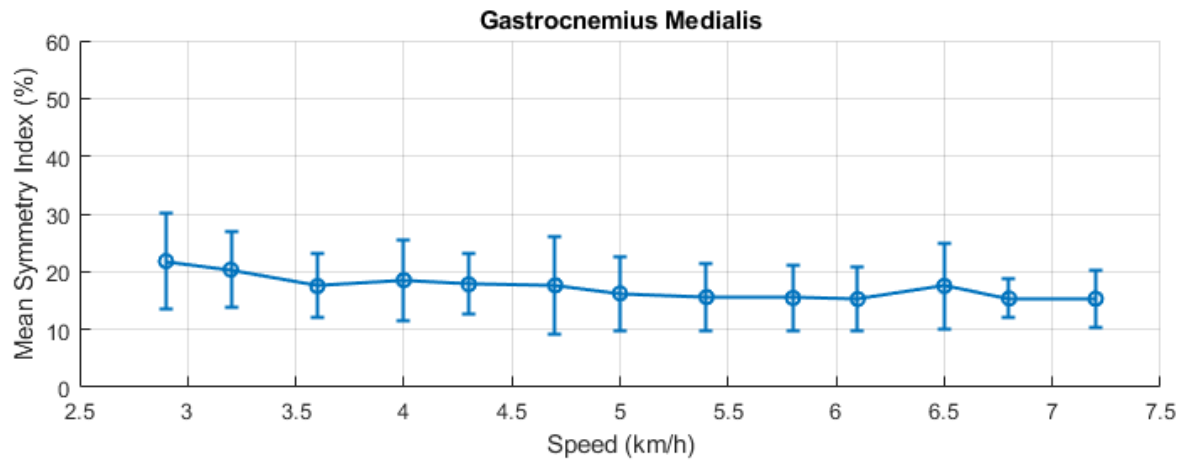


Figure 6. Distribution of mean symmetry index and standard deviation values across speeds for the Gastrocnemius Medialis muscle in 25 participants.

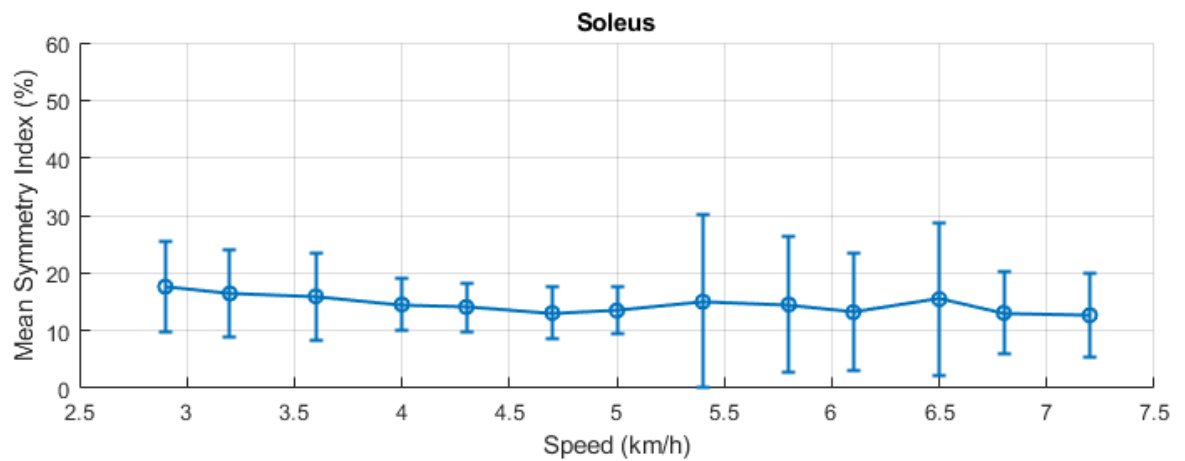


Figure 7. Distribution of mean symmetry index and standard deviation values across speeds for the Soleus muscle in 25 participants.

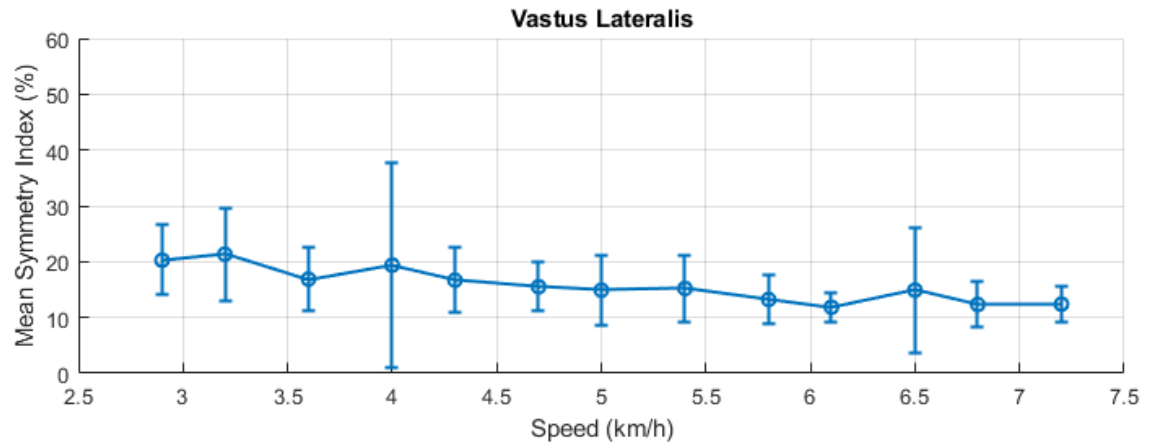


Figure 8. Distribution of mean symmetry index and standard deviation values across speeds for the Vastus Lateralis muscle in 25 participants.

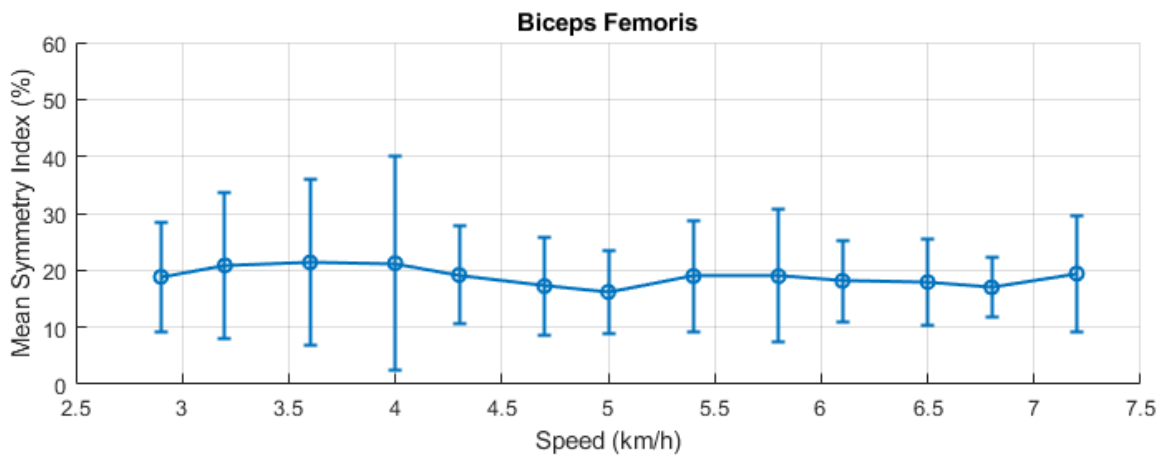


Figure 9. Distribution of mean symmetry index and standard deviation values across speeds for the Biceps Femoris muscle in 25 participants.

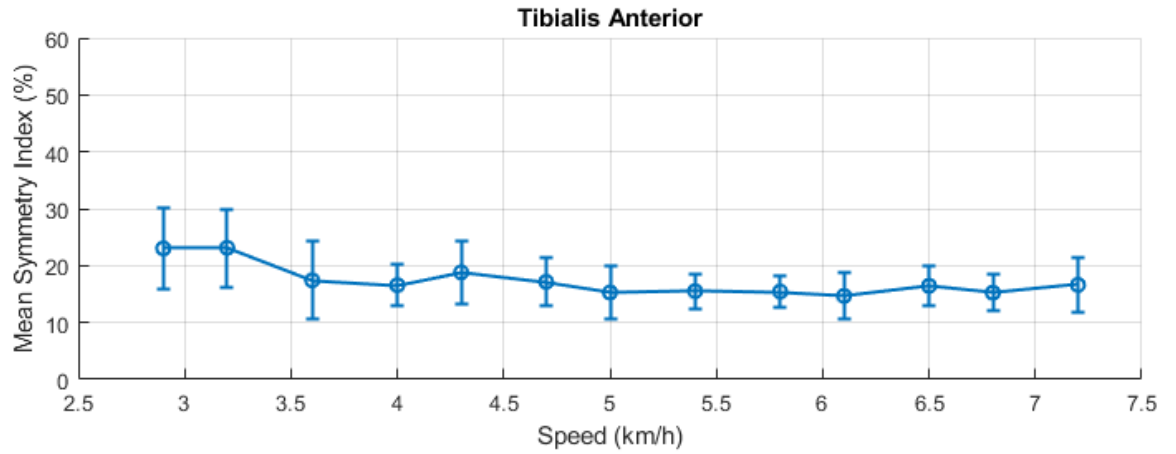


Figure 10. Distribution of mean symmetry index and standard deviation values across speeds for the Tibialis Anterior muscle in 12 participants after outlier removal.

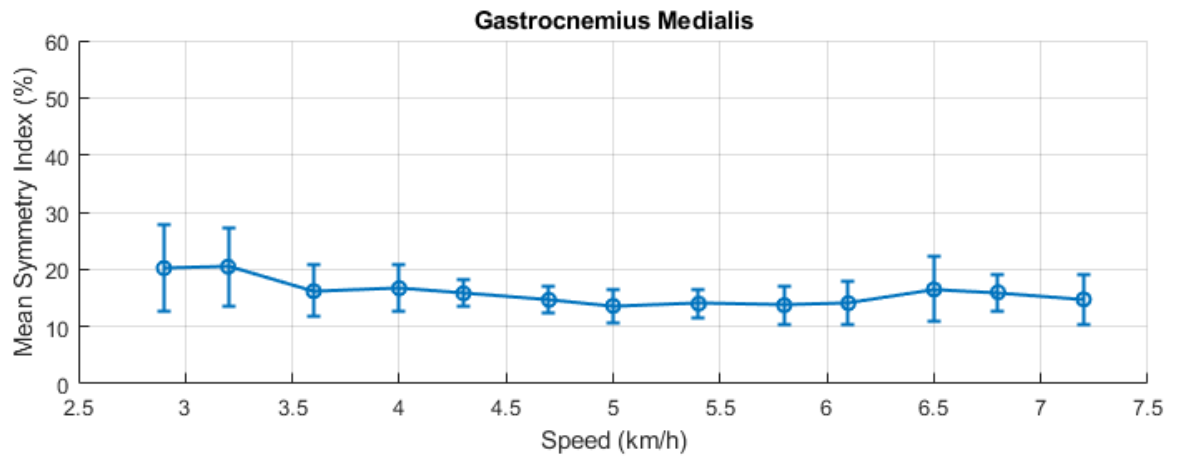


Figure 11. Distribution of mean symmetry index and standard deviation values across speeds for the Gastrocnemius Medialis muscle in 12 participants after outlier removal.

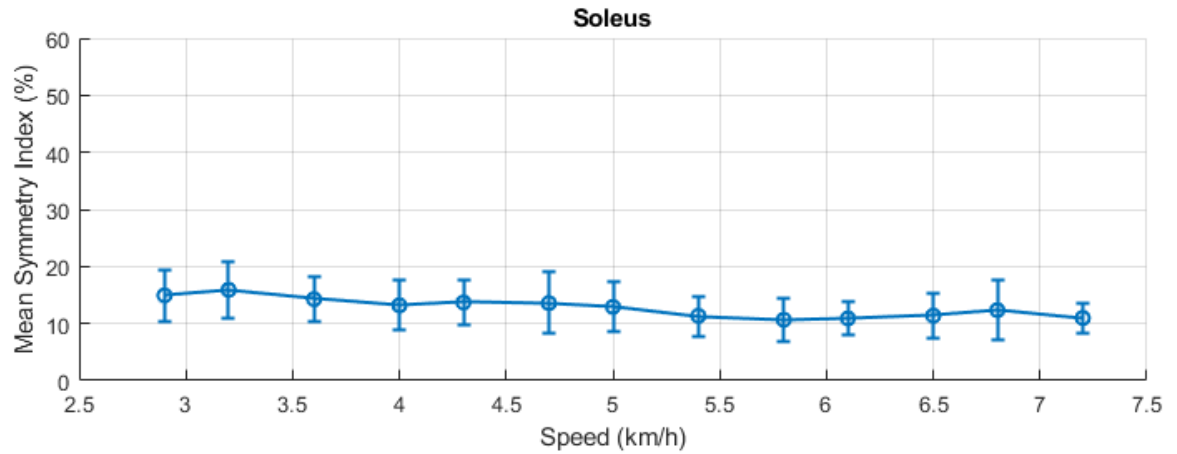


Figure 12. Distribution of mean symmetry index and standard deviation values across speeds for the Soleus muscle in 12 participants after outlier removal.

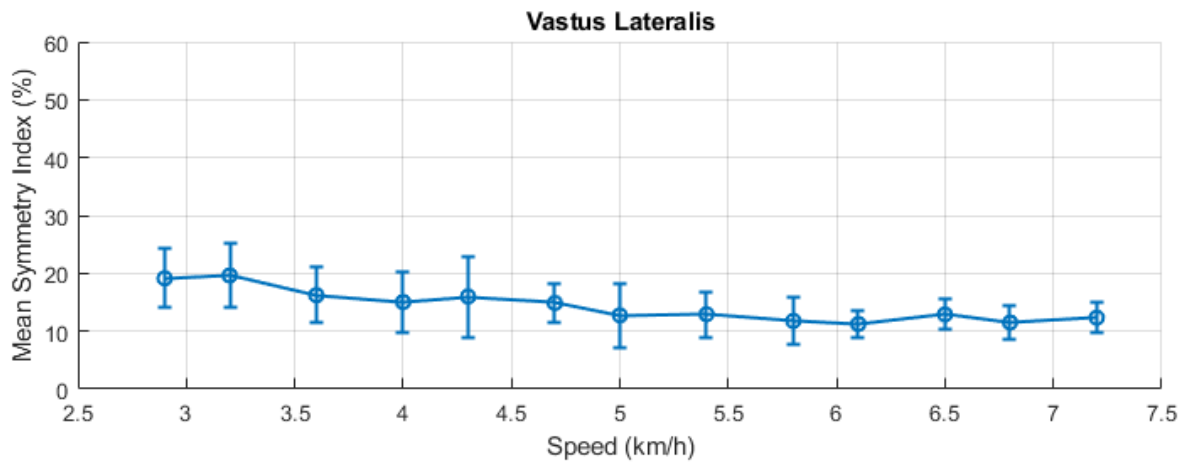


Figure 13. Distribution of mean symmetry index and standard deviation values across speeds for the Vastus Lateralis muscle in 12 participants after outlier removal.

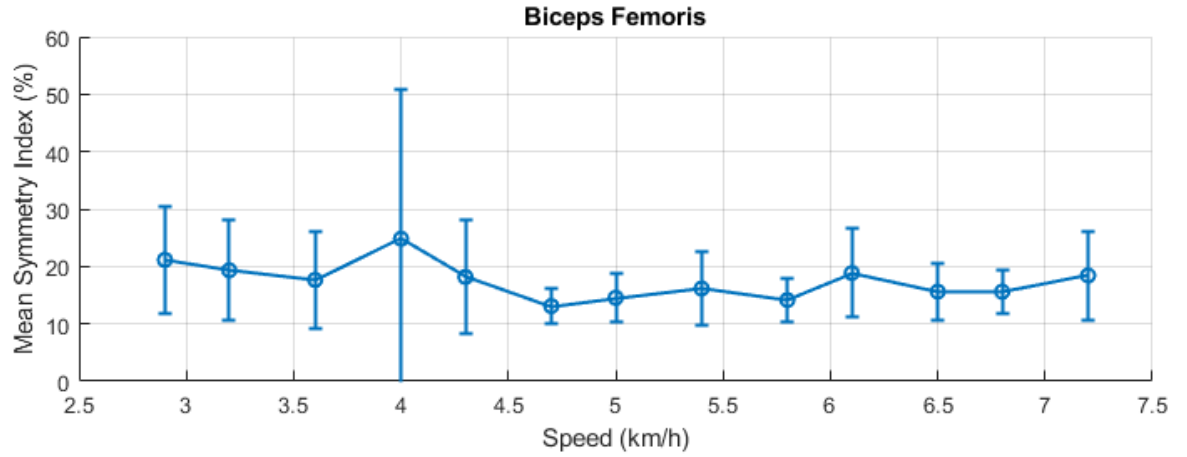


Figure 14. Distribution of mean symmetry index and standard deviation values across speeds for the Biceps Femoris muscle in 12 participants after outlier removal.

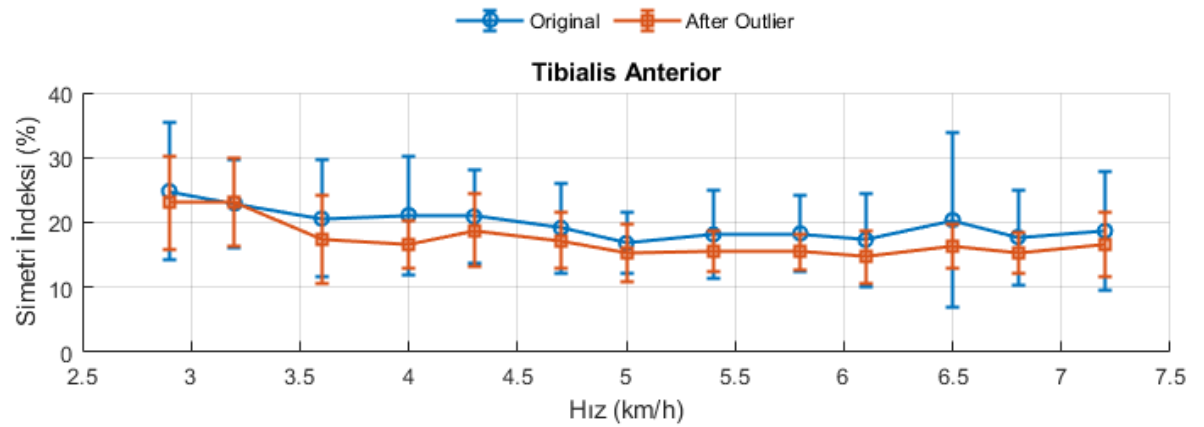


Figure 15. Comparative visualization of mean symmetry index and standard deviation before (25 participants) and after outlier removal (12 participants) for the Tibialis Anterior muscle across walking speeds.

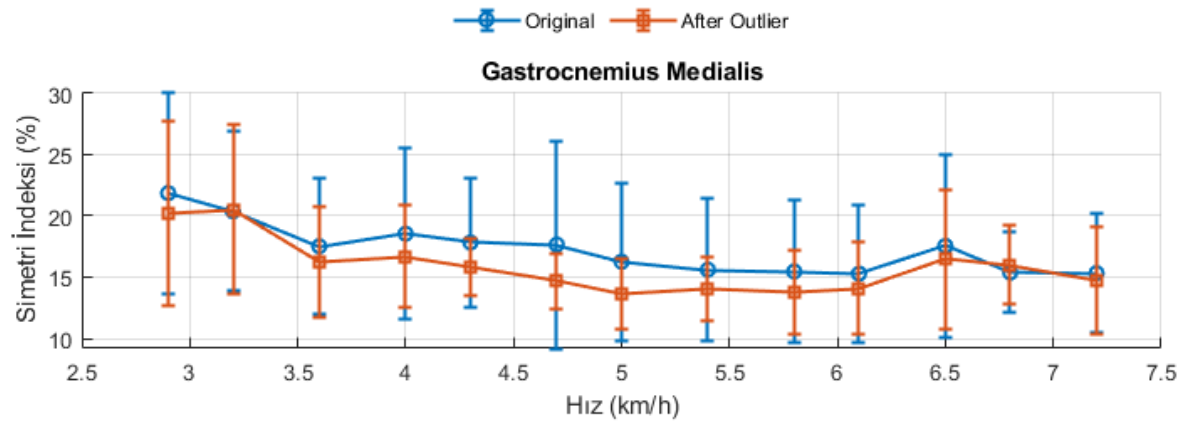


Figure 16. Comparative visualization of mean symmetry index and standard deviation before (25 participants) and after outlier removal (12 participants) for the Gastrocnemius Medialis muscle across walking speeds.

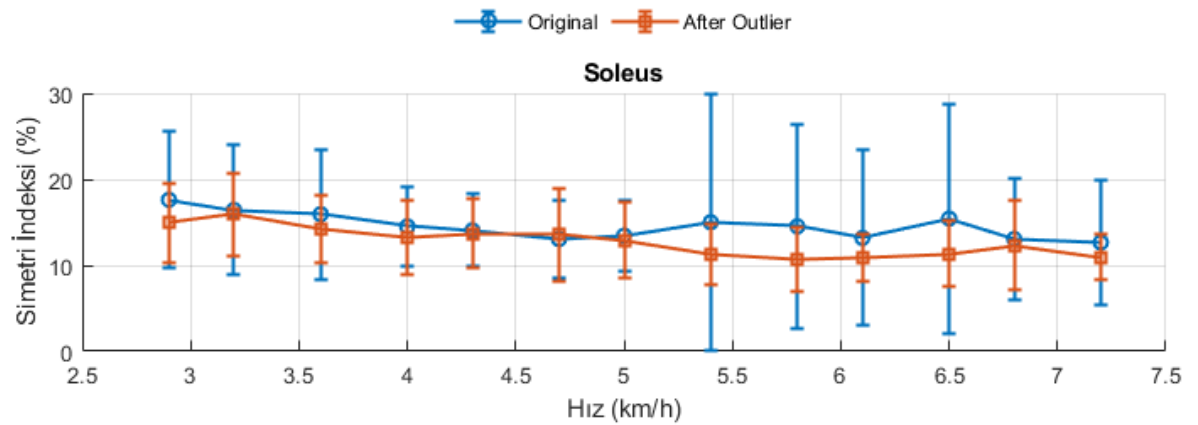


Figure 17. Comparative visualization of mean symmetry index and standard deviation values before (25 participants) and after outlier removal (12 participants) for the Soleus muscle across walking speeds.

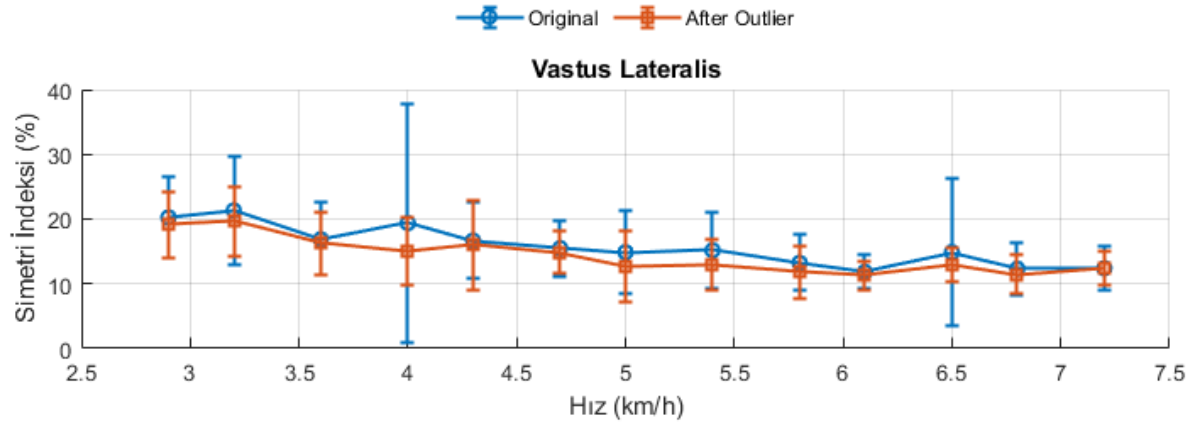


Figure 18. Comparative visualization of mean symmetry index and standard deviation values before (25 participants) and after outlier removal (12 participants) for the Vastus Lateralis muscle across walking speeds.

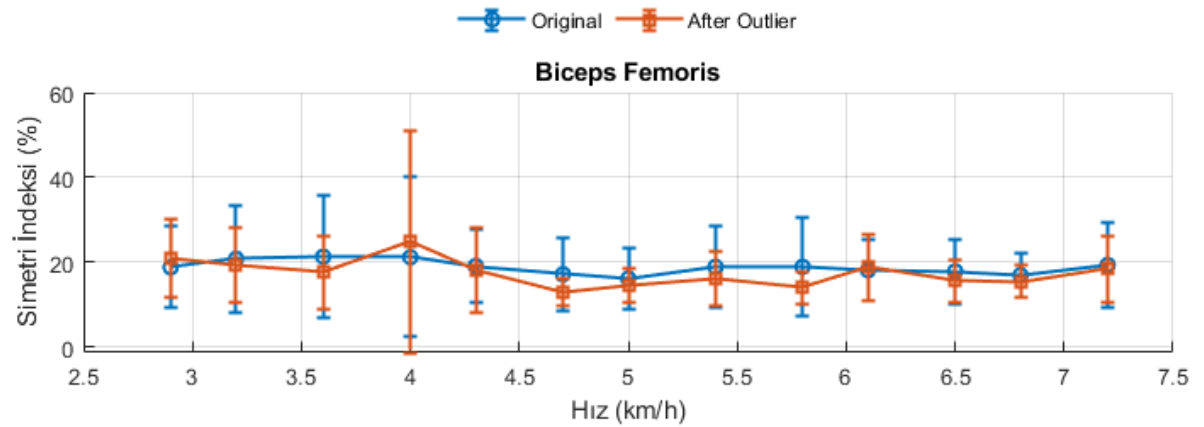


Figure 19. Comparative visualization of mean symmetry index and standard deviation values before (25 participants) and after outlier removal (12 participants) for the Biceps Femoris muscle across walking speeds.

The results obtained in the graphs are also presented numerically in Table 1 and Table 2 with mean $\pm$ standard deviation values for each muscle and speed.

Table 1

Mean Symmetry Index and Standard Deviation Values Before Outlier Removal (25 Participants)

	TA	GAS	SOL	VL	BF
2.9	24.83 $\pm$ 10.59	21.84 $\pm$ 8.26	17.63 $\pm$ 7.93	20.26 $\pm$ 6.25	18.85 $\pm$ 9.57
3.2	22.93 $\pm$ 6.84	20.36 $\pm$ 6.49	16.45 $\pm$ 7.58	21.34 $\pm$ 8.33	20.86 $\pm$ 12.73
3.6	20.60 $\pm$ 9.08	17.51 $\pm$ 5.51	15.96 $\pm$ 7.58	16.88 $\pm$ 5.63	21.37 $\pm$ 14.47
4.0	21.14 $\pm$ 9.18	18.53 $\pm$ 6.93	14.52 $\pm$ 4.61	19.38 $\pm$ 18.45	21.24 $\pm$ 18.80
4.3	20.92 $\pm$ 7.30	17.81 $\pm$ 5.23	14.08 $\pm$ 4.26	16.68 $\pm$ 5.87	19.18 $\pm$ 8.62
4.7	19.16 $\pm$ 6.99	17.64 $\pm$ 8.46	13.06 $\pm$ 4.43	15.50 $\pm$ 4.35	17.22 $\pm$ 8.50
5.0	16.81 $\pm$ 4.64	16.25 $\pm$ 6.43	13.46 $\pm$ 4.06	14.88 $\pm$ 6.33	16.19 $\pm$ 7.19
5.4	18.14 $\pm$ 6.71	15.60 $\pm$ 5.80	15.02 $\pm$ 15.00	15.19 $\pm$ 5.88	18.99 $\pm$ 9.71
5.8	18.30 $\pm$ 5.81	15.45 $\pm$ 5.78	14.54 $\pm$ 11.85	13.23 $\pm$ 4.33	18.97 $\pm$ 11.62
6.1	17.31 $\pm$ 7.24	15.28 $\pm$ 5.56	13.19 $\pm$ 10.23	11.84 $\pm$ 2.67	18.14 $\pm$ 7.13
6.5	20.37 $\pm$ 13.56	17.53 $\pm$ 7.50	15.45 $\pm$ 13.34	14.89 $\pm$ 11.29	17.93 $\pm$ 7.66
6.8	17.74 $\pm$ 7.30	15.36 $\pm$ 3.28	13.07 $\pm$ 7.08	12.32 $\pm$ 4.04	17.00 $\pm$ 5.24
7.2	18.69 $\pm$ 9.12	15.32 $\pm$ 4.90	12.67 $\pm$ 7.31	12.40 $\pm$ 3.31	19.43 $\pm$ 10.15

Table 2

Mean Symmetry Index and Standard Deviation Values After Outlier Removal (12 Participants)

	TA	GAS	SOL	VL	BF
2.9	23.03 $\pm$ 7.13	20.21 $\pm$ 7.56	14.92 $\pm$ 4.53	19.14 $\pm$ 5.16	21.14 $\pm$ 9.22
3.2	23.14 $\pm$ 6.86	20.46 $\pm$ 6.90	15.90 $\pm$ 4.90	19.63 $\pm$ 5.44	19.33 $\pm$ 8.78
3.6	17.42 $\pm$ 6.78	16.19 $\pm$ 4.50	14.27 $\pm$ 3.87	16.22 $\pm$ 4.83	17.65 $\pm$ 8.48
4.0	16.57 $\pm$ 3.61	16.69 $\pm$ 4.12	13.19 $\pm$ 4.30	15.04 $\pm$ 5.22	24.83 $\pm$ 26.03
4.3	18.82 $\pm$ 5.58	15.81 $\pm$ 2.28	13.69 $\pm$ 4.01	15.99 $\pm$ 7.02	18.16 $\pm$ 9.90
4.7	17.15 $\pm$ 4.29	14.66 $\pm$ 2.31	13.57 $\pm$ 5.41	14.87 $\pm$ 3.23	13.09 $\pm$ 3.18
5.0	15.27 $\pm$ 4.54	13.62 $\pm$ 2.87	12.91 $\pm$ 4.41	12.75 $\pm$ 5.51	14.54 $\pm$ 4.15

Table 2 (cont'd)

5.4	15.51 ± 3.12	13.99 ± 2.58	11.35 ± 3.50	12.93 ± 3.93	16.16 ± 6.39
5.8	15.43 ± 2.83	13.73 ± 3.39	10.66 ± 3.75	11.77 ± 4.17	14.14 ± 3.76
6.1	14.66 ± 4.14	14.10 ± 3.76	10.89 ± 2.81	11.25 ± 2.22	18.85 ± 7.71
6.5	16.45 ± 3.39	16.48 ± 5.67	11.37 ± 3.81	12.88 ± 2.58	15.61 ± 4.89
6.8	15.23 ± 3.14	15.99 ± 3.21	12.34 ± 5.14	11.50 ± 2.89	15.59 ± 3.86
7.2	16.62 ± 4.93	14.75 ± 4.37	10.97 ± 2.60	12.33 ± 2.63	18.42 ± 7.67

4.2 Feature-Based Symmetry Analysis Across Walking Speeds

4.2.1 MAV feature. SI and Standard Deviation: (Table 3) presents the mean symmetry index and standard deviation (SD) values for each muscle and walking speed. MAV-based symmetry analysis at different walking speeds revealed remarkable differences between muscles. The visual equivalent of these values is presented in Figure 20.

Table 3

Mean and Standard Deviation of Symmetry Index Values in Each Muscle at Different Walking Speeds – MAV Feature Analysis

	TA	GAS	SOL	VL	BF
2.9 km/h	23.03 ± 7.13	20.21 ± 7.56	14.92 ± 4.53	19.14 ± 5.16	21.14 ± 9.22
3.2 km/h	23.14 ± 6.86	20.46 ± 6.90	15.90 ± 4.90	19.63 ± 5.44	19.33 ± 8.78
3.6 km/h	17.42 ± 6.78	16.19 ± 4.50	14.27 ± 3.87	16.22 ± 4.83	17.65 ± 8.48
4.0 km/h	16.57 ± 3.61	16.69 ± 4.12	13.19 ± 4.30	15.04 ± 5.22	24.83 ± 26.03
4.3 km/h	18.82 ± 5.58	15.81 ± 2.28	13.69 ± 4.01	15.99 ± 7.02	18.16 ± 9.90
4.7 km/h	17.15 ± 4.29	14.66 ± 2.31	13.57 ± 5.41	14.87 ± 3.23	13.09 ± 3.18
5.0 km/h	15.27 ± 4.54	13.62 ± 2.87	12.91 ± 4.41	12.75 ± 5.51	14.54 ± 4.15
5.4 km/h	15.51 ± 3.12	13.99 ± 2.58	11.35 ± 3.50	12.93 ± 3.93	16.16 ± 6.39
5.8 km/h	15.43 ± 2.83	13.73 ± 3.39	10.66 ± 3.75	11.77 ± 4.17	14.14 ± 3.76
6.1 km/h	14.66 ± 4.14	14.10 ± 3.76	10.89 ± 2.81	11.25 ± 2.22	18.85 ± 7.71
6.5 km/h	16.45 ± 3.39	16.48 ± 5.67	11.37 ± 3.81	12.88 ± 2.58	15.61 ± 4.89
6.8 km/h	15.23 ± 3.14	15.99 ± 3.21	12.34 ± 5.14	11.50 ± 2.89	15.59 ± 3.86

Table 3 (cont'd)

7.2 km/h	16.62 ± 4.93	14.75 ± 4.37	10.97 ± 2.60	12.33 ± 2.63	18.42 ± 7.67
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While the TA muscle has a high symmetry index at low speeds (e.g. $23.03 \pm 7.13\%$ at 2.9 km/h), this value decreases towards 5.0 km/h and becomes relatively constant. Similarly, a significant decrease was observed in the GM muscle, the value which was $20.21 \pm 7.56\%$ at 2.9 km/h decreased to $13.62 \pm 2.87\%$ at 5.0 km/h. The SOL muscle stood out as the muscle with the lowest symmetry index values in general, and the value decreased further as the walking speed increased. The VL muscle also exhibited a similar trend, with the symmetry index decreasing as the speed increased. For the BF muscle, the high variance observed at 4.0 km/h ($24.83 \pm 26.03\%$) indicates that there are high inter-individual symmetry differences in this muscle.

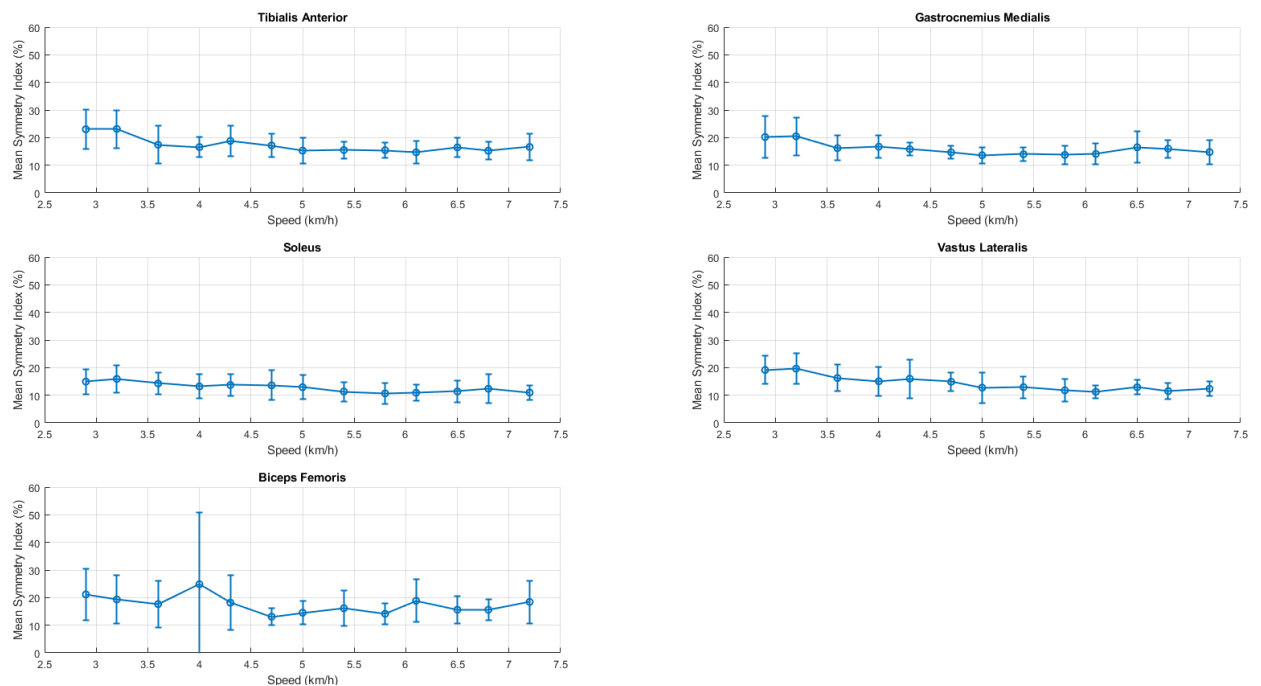


Figure 20. Percent changes in the symmetry index of lower limb muscles across different walking speeds – MAV feature analysis

ANOVA Results: One-way ANOVA analysis showed that there was a statistically significant difference in terms of symmetry index between different speed groups in TA

($p = 0.0000$), GM ($p = 0.0007$), SOL ($p = 0.0329$) and VL ($p = 0.0000$) muscles. In the analysis conducted only for BF muscle, no significant difference was found between speed groups ($p = 0.2440$).

Post Hoc Comparisons: In cases where statistically significant differences are detected after one-way ANOVA analysis for each muscle, Tukey-Kramer post hoc tests are applied to reveal whether there is a significant difference between certain speed pairs. The findings of these tests are visually presented in Figures 21–22 to show the statistical differences between the relevant speed groups. In the graphs, the blue group represents the reference speed in the comparisons; the groups shown in red represent the speeds that show statistically significant differences ($p < 0.05$). The gray groups represent the levels that do not show significant differences. In addition, the numerical results including the mean difference (Estimate), confidence intervals (LowerCI – UpperCI) and p-values for this analysis are presented in Tables 4–6. Additionally, speed pairs with significant differences were also visualized using a heatmap as shown in Figures 23–25.

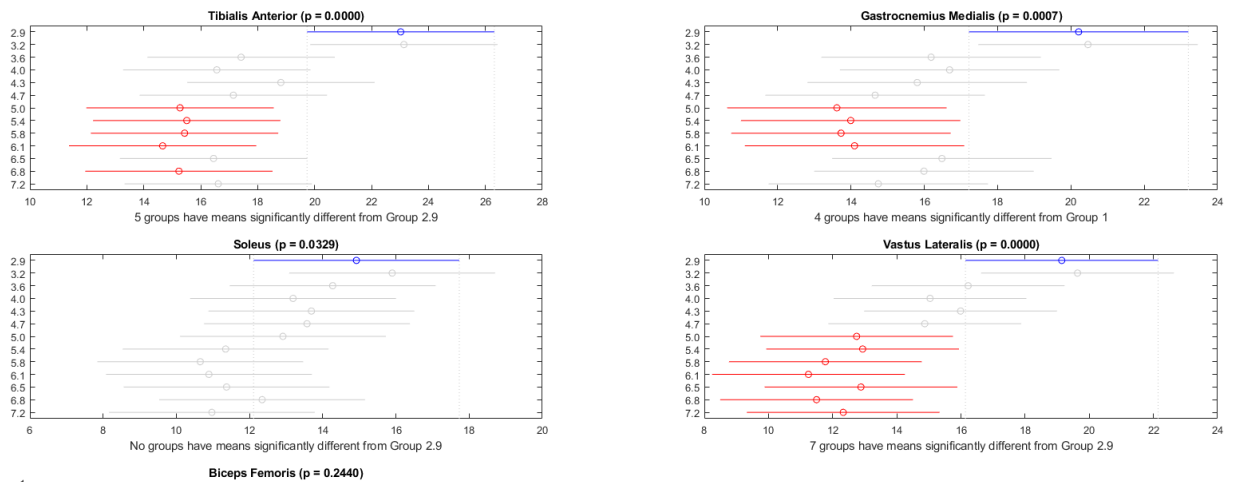


Figure 21. Post hoc comparison results of Tibialis Anterior, Gastrocnemius Medialis, Soleus and Vastus Lateralis muscles (reference speed: 2.9 km/h) – MAV feature analysis.

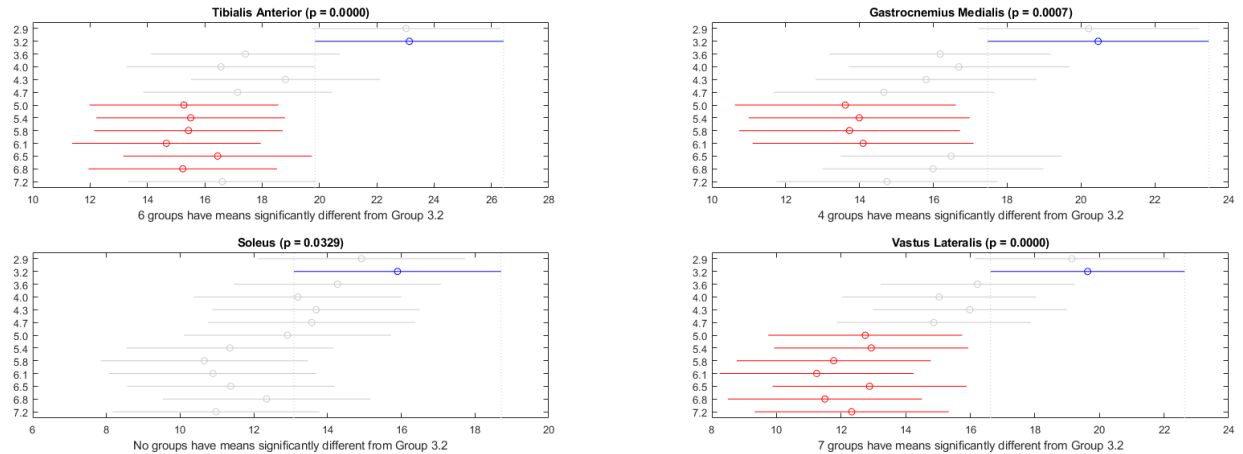


Figure 22. Post hoc comparison results of Tibialis Anterior, Gastrocnemius Medialis, Soleus and Vastus Lateralis muscles (reference speed: 3.2 km/h) – MAV feature analysis

Post hoc comparison results of TA muscle showed that individuals walking at 2.9 km/h had significantly higher symmetry index values compared to individuals walking at 5.0, 5.4, 5.8, 6.1 and 6.8 km/h ($p < 0.05$). Similarly, 3.2 km/h speed had significantly higher means than those walking at 5.0, 5.4, 5.8, 6.1, 6.5 and 6.8 km/h ($p < 0.05$) (Table 4).

Table 4

Symmetry Index Differences Across Walking Speeds for Tibialis Anterior Muscle – Post Hoc Results (MAV Feature, Speed: km/h)

Speed 1	Speed 2	Estimate	LowerCI	UpperCI	pValue
2.9	5.0	7.75	1.17	14.33	0.006
2.9	5.4	7.52	0.94	14.10	0.010
2.9	5.8	7.59	1.01	14.17	0.009
2.9	6.1	8.36	1.78	14.94	0.002
2.9	6.8	7.79	1.21	14.37	0.006
3.2	5.0	7.86	1.28	14.44	0.005
3.2	5.4	7.62	1.05	14.20	0.008
3.2	5.8	7.70	1.12	14.28	0.007
3.2	6.1	8.47	1.89	15.05	0.001
3.2	6.5	6.69	0.10	13.26	0.042

Table 4 (cont'd)

3.2	6.8	7.90	1.32	14.48	0.005
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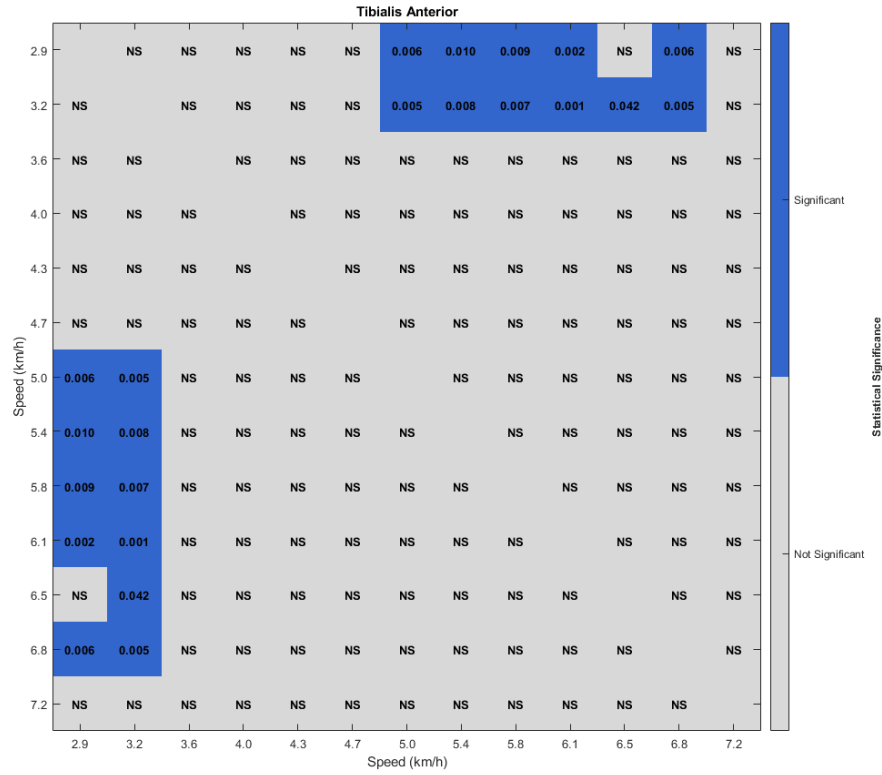


Figure 23. Post-hoc pairwise statistical significance matrix of symmetry index for Tibialis Anterior – MAV feature analysis

According to the comparison results in the GM muscle, statistically significant differences in muscle activity were observed between the speeds of 2.9 km/h and 3.2 km/h and 5.0, 5.4, 5.8, 6.1 km/h ($p < 0.05$) (Table 5). This finding shows that muscle activity changes significantly as walking speed increases.

Table 5

Symmetry Index Differences Across Walking Speeds for Gastrocnemius Medialis Muscle – Post Hoc Results (MAV Feature, Speed: km/h)

Speed 1	Speed 2	Estimate	LowerCI	UpperCI	pValue
2.9	5.0	6.59	0.61	12.58	0.016
2.9	5.4	6.22	0.23	12.20	0.033
2.9	5.8	6.48	0.50	12.47	0.020
2.9	6.1	6.11	0.13	12.10	0.040
3.2	5.0	6.85	0.86	12.83	0.010
3.2	5.4	6.47	0.49	12.46	0.021
3.2	5.8	6.74	0.75	12.72	0.012
3.2	6.1	6.37	0.38	12.35	0.025

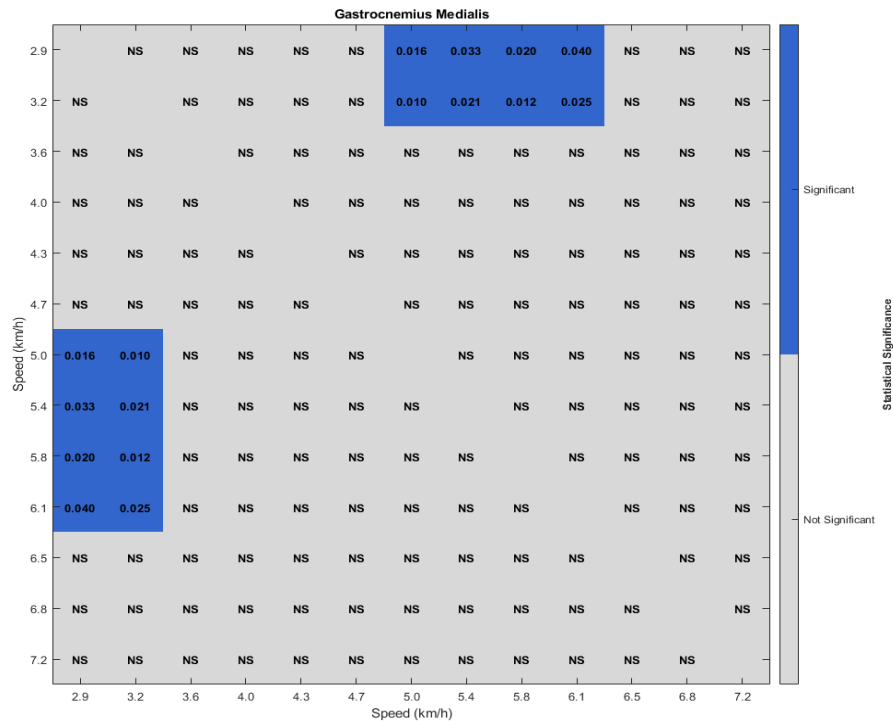


Figure 24. Post-hoc pairwise statistical significance matrix of symmetry index for Gastrocnemius Medialis – MAV feature analysis

In the analysis of variance for the SOL muscle, the general difference between the groups was found to be significant ($p = 0.0329$). However, in the post hoc analysis, no paired group was found to reach statistical significance because of multiple comparisons (Tukey HSD, $p > 0.05$). This shows that the difference exists in general, but it is statistically difficult to determine which group pairs it is specifically between.

According to the post hoc analysis results, walking speeds of 2.9 km/h and 3.2 km/h had significantly higher symmetry index values in the Vastus Lateralis muscle compared to speeds between 5.0 and 7.2 km/h ($p < 0.05$) (Table 6). These comparisons show that lower speeds are statistically different compared to other speeds.

Table 6

Symmetry Index Differences Across Walking Speeds for Vastus Lateralis Muscle – Post Hoc Results (MAV Feature, Speed: km/h)

Speed 1	Speed 2	Estimate	LowerCI	UpperCI	pValue
2.9	5.0	6.40	0.39	12.40	0.025
2.9	5.4	6.21	0.20	12.22	0.035
2.9	5.8	7.37	1.36	13.38	0.003
2.9	6.1	7.90	1.89	13.91	0.001
2.9	6.5	6.26	0.25	12.27	0.032
2.9	6.8	7.64	1.64	13.65	0.002
2.9	7.2	6.81	0.81	12.82	0.011
3.2	5.0	6.89	0.88	12.89	0.009
3.2	5.4	6.70	0.69	12.71	0.014
3.2	5.8	7.86	1.85	13.87	0.001
3.2	6.1	8.39	2.38	14.40	0.000
3.2	6.5	6.75	0.74	12.76	0.012
3.2	6.8	8.14	2.13	14.14	0.001
3.2	7.2	7.30	1.30	13.31	0.004

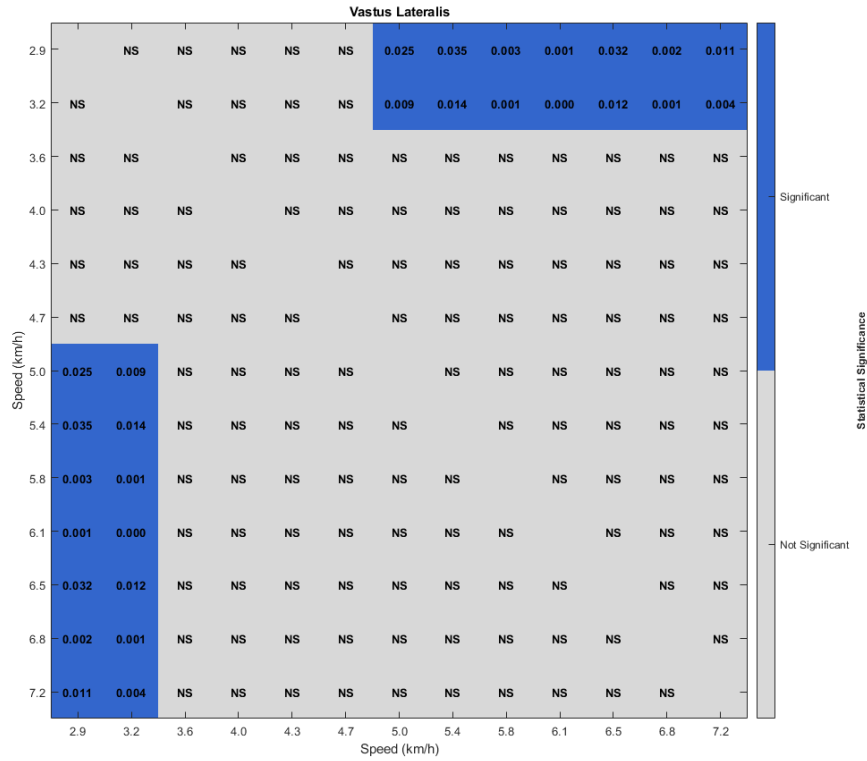


Figure 25. Post-hoc pairwise statistical significance matrix of symmetry index for Vastus Lateralis – MAV feature analysis

4.2.2 AR feature. Descriptive statistics of SI and Standard Deviation present the mean symmetry index and standard deviation (SD) values for each muscle and walking speed (Table 7). AR-based symmetry analysis at different walking speeds revealed differences between muscles. The visual equivalent of these values is presented in Figure 26.

Table 7

Mean and Standard Deviation of Symmetry Index Values in Each Muscle at Different Walking Speeds – AR Feature Analysis

	TA	GAS	SOL	VL	BF
2.9 km/h	1.57 ± 1.07	1.42 ± 0.83	1.03 ± 0.47	1.00 ± 0.19	1.90 ± 1.23
3.2 km/h	4.66 ± 10.32	4.55 ± 10.27	5.44 ± 14.82	7.91 ± 22.04	2.28 ± 1.29
3.6 km/h	1.79 ± 0.98	1.12 ± 0.46	0.83 ± 0.38	0.96 ± 0.35	1.31 ± 0.82
4.0 km/h	1.13 ± 0.42	0.82 ± 0.29	0.75 ± 0.42	1.02 ± 0.60	1.26 ± 0.64
4.3 km/h	1.36 ± 0.80	0.93 ± 0.39	0.63 ± 0.28	0.69 ± 0.22	1.25 ± 0.60
4.7 km/h	0.92 ± 0.52	0.77 ± 0.33	0.61 ± 0.18	0.93 ± 0.35	0.96 ± 0.61
5.0 km/h	0.97 ± 0.73	0.68 ± 0.37	0.48 ± 0.18	0.80 ± 0.31	0.99 ± 0.88
5.4 km/h	0.96 ± 0.63	0.69 ± 0.37	0.59 ± 0.32	0.80 ± 0.21	1.14 ± 0.83
5.8 km/h	0.74 ± 0.31	0.69 ± 0.31	0.44 ± 0.17	0.64 ± 0.25	0.99 ± 0.81
6.1 km/h	0.68 ± 0.37	0.83 ± 0.70	0.46 ± 0.23	0.75 ± 0.38	0.85 ± 0.50
6.5 km/h	0.71 ± 0.22	0.67 ± 0.46	0.45 ± 0.26	0.64 ± 0.25	0.75 ± 0.42
6.8 km/h	0.74 ± 0.41	0.56 ± 0.23	0.43 ± 0.14	0.60 ± 0.31	0.72 ± 0.29
7.2 km/h	0.71 ± 0.50	1.02 ± 1.23	0.41 ± 0.19	0.65 ± 0.40	0.62 ± 0.23

In the TA muscle, the Symmetry Index (SI) value reached the highest level at 3.2 km/h speed with 4.66 and standard deviation (SD) 10.32. This value shows that the TA muscle works quite asymmetrically and varies between individuals at low speed. While the SI was observed as 1.57 ± 1.07 at 2.9 km/h, a significant decrease was observed in the SI values as the walking speed increased, and for 6.1 km/h and later, the SI values were fixed between 0.68 - 0.74, and the SD values were fixed between 0.22 - 0.41. This situation shows that the TA muscle works symmetrically at higher speeds.

Similarly, the highest asymmetry was observed at 3.2 km/h in the GM muscle (SI: 4.55 ± 10.27). As the walking speed increased, both SI and SD values showed a regular decreasing trend. While the SI value was measured between 0.56 and 1.02 in the 6.8 - 7.2 km/h range, the SD values decreased to 0.23 - 1.23. This shows that more symmetrical activity occurs in the GM muscle with speed.

In the SOL muscle, the highest SI and SD values were recorded at 3.2 km/h at 5.44 ± 14.82 among all speeds. This shows that both the highest asymmetry and inter-participant variation occur in this muscle at low speed. At 5.8 km/h and later, SI values decreased to 0.41 – 0.46, SD values decreased to 0.14 – 0.23 and gained significant stability.

Maximum asymmetry and variation in the VL muscle was also measured at 3.2 km/h (SI: 7.91 ± 22.04). This extraordinarily high variation reveals that the VL muscle works quite unbalanced at low speeds. As we moved to high speeds, SI and SD values decreased and reached SI: 0.60 – 0.65, SD: 0.25 – 0.40 in the 6.5 – 7.2 km/h range.

A different trend was observed in the BF muscle. The highest SI value was measured as 0.99 ± 0.88 at 5.0 km/h. Generally, lower SI and SD values were obtained compared to other muscles. At 7.2 km/h, the SI value was recorded as 0.62 and the SD as 0.23. This suggests that the BF muscle is generally more balanced but shows slight fluctuations in the range of 3.2 – 5.4 km/h.

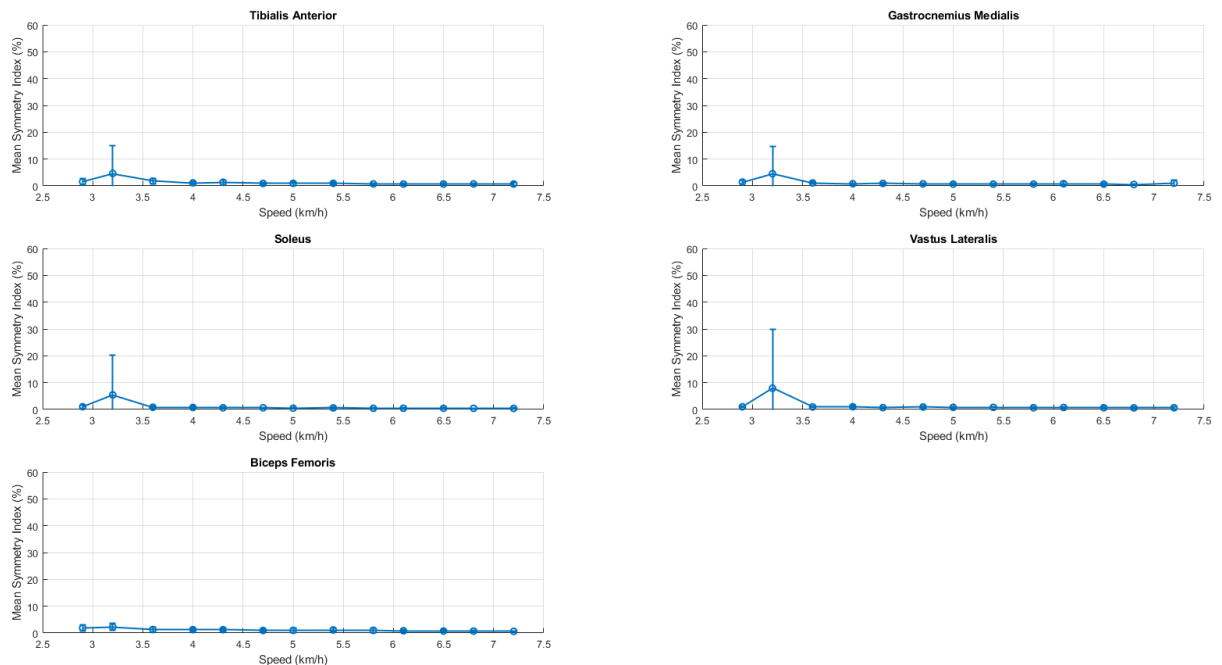


Figure 26. Percent changes in the symmetry index of lower limb muscles across different walking speeds – AR feature analysis

According to the one-way ANOVA analysis performed to determine whether the SI values showed a significant change at different walking speeds, no statistically significant difference was found in the TA ($p = 0.0980$), GM ($p = 0.1046$), SOL ($p = 0.2239$) and VL ($p = 0.2519$) muscles ($p > 0.05$). The $p = 0.0000$ value obtained for the BF muscle reveals a significant relationship between walking speed and symmetry index ($p < 0.05$). This result indicates that the BF muscle shows significant differences in symmetric activity levels at different walking speeds.

The findings of the Tukey-Kramer post hoc test applied to the BF muscle, for which a statistically significant difference was detected as a result of the one-way ANOVA analysis, are presented visually in Figures 27-28 and numerically in Table 8, showing the significant differences between the relevant speed groups. Figure 29 presented speed pairs with significant differences and visualized using a heatmap.

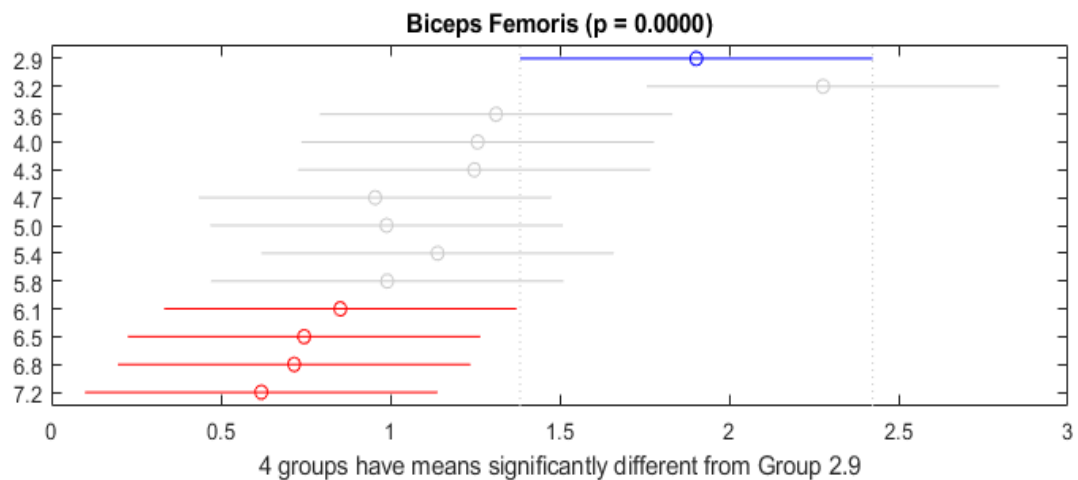


Figure 27. Post-hoc comparison of Biceps Femoris muscle across walking speeds based on AR feature: Group 2.9 km/h shows statistically significant differences with groups 6.1, 6.5, 6.8, and 7.2 km/h ($p < 0.05$).

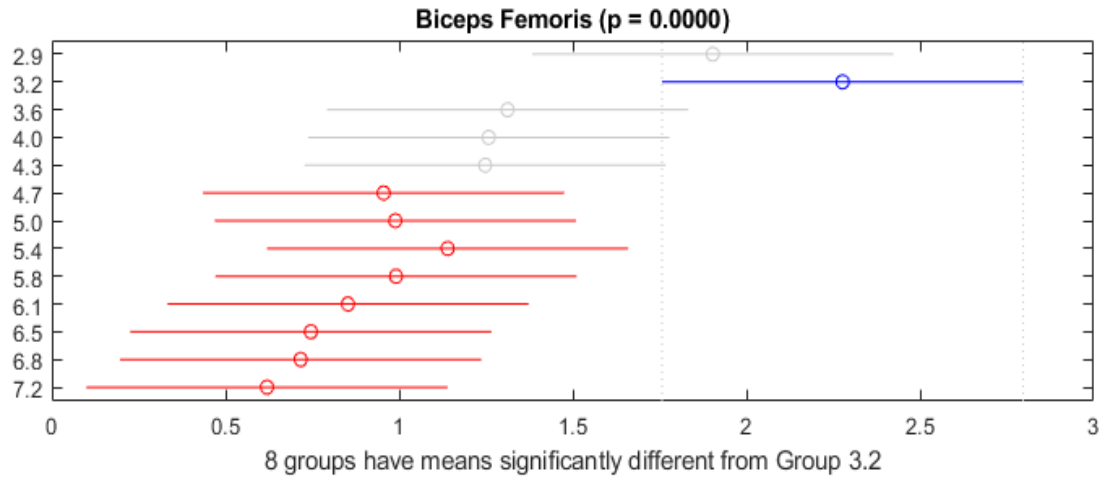


Figure 28. Post-hoc comparison of Biceps Femoris muscle across walking speeds based on AR feature: Group 3.2 km/h shows statistically significant differences with groups 4.7, 5.0, 5.4, 5.8, 6.1, 6.5, 6.8, and 7.2 km/h ($p < 0.05$).

Table 8

Symmetry Index Differences Across Walking Speeds for Biceps Femoris Muscle – Post Hoc Results (AR Feature, Speed: km/h)

Speed 1	Speed 2	Estimate	LowerCI	UpperCI	pValue
2.9	6.1	1.05	0.01	2.09	0.045
2.9	6.5	1.16	0.12	2.20	0.014
2.9	6.8	1.19	0.15	2.23	0.01
2.9	7.2	1.28	0.24	2.32	0.003
3.2	4.7	1.32	0.28	2.36	0.0018
3.2	5.0	1.29	0.25	2.33	0.0028
3.2	5.4	1.24	0.10	2.18	0.0178
3.2	5.8	1.29	0.25	2.33	0.0029
3.2	6.1	1.42	0.38	2.46	$p < 0.001$
3.2	6.5	1.53	0.49	2.57	$p < 0.001$
3.2	6.8	1.56	0.52	2.60	$p < 0.001$
3.2	7.2	1.66	0.62	2.70	$p < 0.001$

When all walking speeds were compared with each other, statistically significant differences in symmetry index were observed especially between low speeds (2.9 and 3.2 km/h) and high speeds (6.1 km/h and above) ($p < 0.05$). However, no significant difference was observed in the comparisons between medium speeds (3.6–5.4 km/h). These results show that the symmetry index is more variable at low speeds and more stable at medium and high speeds.

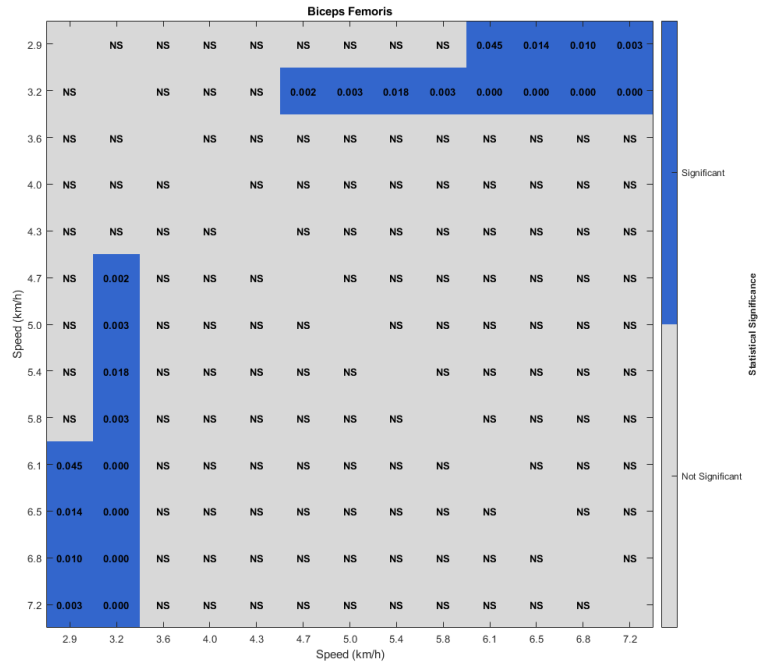


Figure 29. Post-hoc pairwise statistical significance matrix of symmetry index for Biceps Femoris – AR feature analysis

4.2.3 RMS feature. Descriptive Statistics of SI and Standard Deviation: (Table 9) presents the RMS-based mean symmetry index (Mean Symmetry Index) and standard deviation (SD) values for each muscle and walking speed. The visual equivalent of these values is presented in Figure 30.

Table 9

Mean and Standard Deviation of Symmetry Index Values in Each Muscle at Different Walking Speeds – RMS Feature Analysis

	TA	GAS	SOL	VL	BF
2.9 km/h	23.59 ± 6.56	19.47 ± 6.43	16.43 ± 5.27	19.10 ± 4.73	26.96 ± 13.04
3.2 km/h	23.22 ± 7.41	19.49 ± 6.77	16.32 ± 4.45	17.83 ± 4.20	22.23 ± 11.89
3.6 km/h	19.78 ± 8.69	15.58 ± 4.14	14.56 ± 5.73	15.81 ± 4.09	21.17 ± 14.29
4.0 km/h	18.76 ± 3.23	16.58 ± 4.55	13.79 ± 3.75	15.01 ± 4.14	26.10 ± 22.91
4.3 km/h	20.18 ± 5.95	15.75 ± 3.19	13.11 ± 3.93	15.00 ± 5.73	19.99 ± 13.05
4.7 km/h	17.54 ± 3.61	15.49 ± 3.56	13.41 ± 4.97	14.32 ± 2.51	15.24 ± 5.14
5.0 km/h	16.32 ± 3.28	13.71 ± 2.67	13.34 ± 4.32	12.54 ± 3.96	18.48 ± 10.14
5.4 km/h	15.82 ± 2.90	14.00 ± 2.62	11.94 ± 4.64	13.95 ± 2.65	19.99 ± 13.10
5.8 km/h	15.07 ± 2.22	14.40 ± 3.86	10.52 ± 2.70	13.10 ± 3.73	17.22 ± 7.08
6.1 km/h	15.01 ± 2.89	14.85 ± 3.77	11.60 ± 3.24	12.02 ± 2.54	21.17 ± 11.14
6.5 km/h	17.16 ± 4.59	18.27 ± 6.95	12.85 ± 4.97	13.41 ± 2.69	15.75 ± 3.30
6.8 km/h	14.89 ± 2.59	18.08 ± 5.04	13.07 ± 4.47	12.03 ± 3.02	16.96 ± 4.21
7.2 km/h	16.64 ± 3.48	16.92 ± 5.20	12.91 ± 2.53	12.62 ± 2.26	18.64 ± 4.19

In the TA muscle, the highest mean symmetry index value was measured as 23.59 ± 6.56 at 2.9 km/h. This value showed a general decreasing trend depending on speed. The lowest mean was found as 14.89 ± 2.59 at 6.8 km/h. This situation shows that walking at low speed may affect the symmetry in the TA muscle more.

In the GM muscle, similar symmetry indices were observed at 2.9 and 3.2 km/h speeds (19.47 ± 6.43 and 19.49 ± 6.77). However, there was a significant decrease in these values between 5.0 and 5.8 km/h. The lowest value was measured as 13.71 ± 2.67 at 5.0

km/h; then it increased again at 6.5 and 6.8 km/h speeds (18.27 ± 6.95 , 18.08 ± 5.04). This shows that the muscle may become more unbalanced in terms of symmetry with increasing speed.

The average symmetry index for the SOL muscle was determined as 16.43 ± 5.27 at the highest 2.9 km/h. A decrease was observed in this value with increasing speed. It decreased to a minimum especially at 5.8 km/h and was determined as 10.52 ± 2.70 . However, the value increased again at 6.5 km/h (12.85 ± 4.97), did not show a constant trend as walking speed changed, and did not exhibit a symmetry index that constantly increased or decreased as speed increased.

In the VL muscle, generally low symmetry index values were observed. However, relatively high averages such as 19.10 ± 4.73 at 2.9 km/h, 17.83 ± 4.20 at 3.2 km/h and 15.01 ± 4.14 at 4.0 km/h were determined. In particular, the lowest value of 12.03 ± 3.02 was measured at 6.8 km/h. It is seen that the symmetry values of this muscle show more variability at low and medium speeds and are more stable at high speeds.

In the BF muscle, the highest average value was measured at 2.9 km/h with 26.96 ± 13.04 , and a high standard deviation was also observed at this speed. The value at 4.0 km/h (26.10 ± 22.91) supports this situation. The lowest value was found as 15.24 ± 5.14 at 4.7 km/h. High variations were generally observed for this muscle, and it is notable for high standard deviations even at medium speeds.

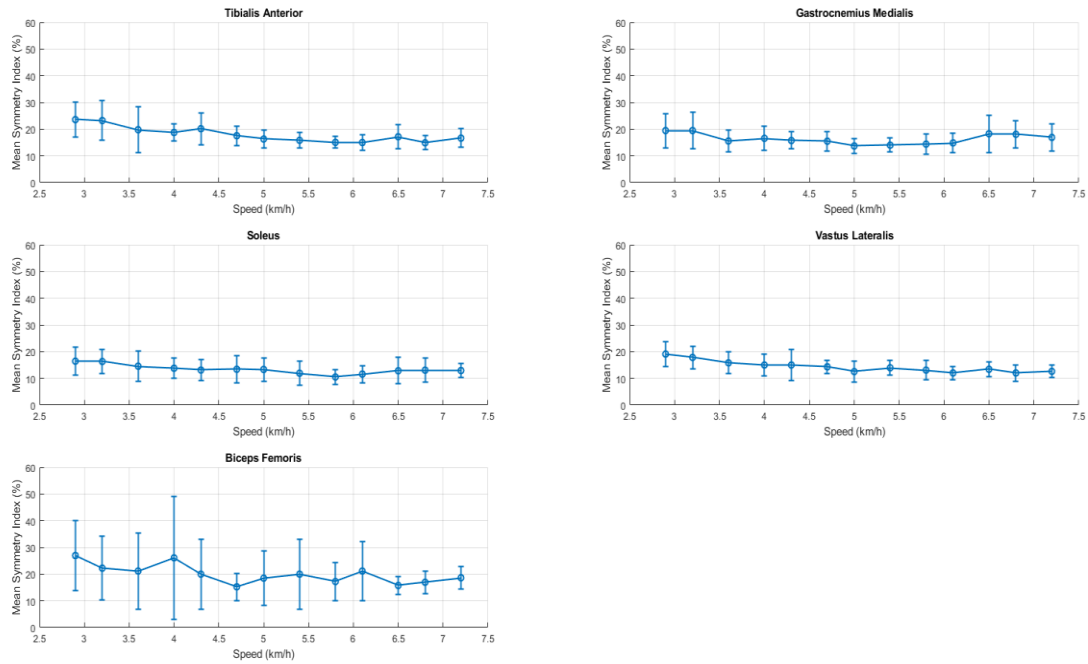


Figure 30. Percent changes in the symmetry index of lower limb muscles across different walking speeds – RMS feature analysis

ANOVA Results: One-way ANOVA analysis showed that there was a statistically significant difference in terms of symmetry index between different speed groups in Tibialis Anterior ($p = 0.0000$), Gastrocnemius Medialis ($p = 0.0212$), Vastus Lateralis ($p = 0.0000$) muscles. In the analysis performed for Soleus ($p = 0.546$) and Biceps Femoris muscle ($p = 0.3144$), no significant difference was found between speed groups.

The findings of the Tukey-Kramer post hoc test applied for the muscles in which statistically significant differences were detected because of one-way ANOVA analysis are presented visually in Figures 31–34, numerically in Tables 10–11, and these significant speed pair differences are also illustrated as heatmaps in Figures 35–36.

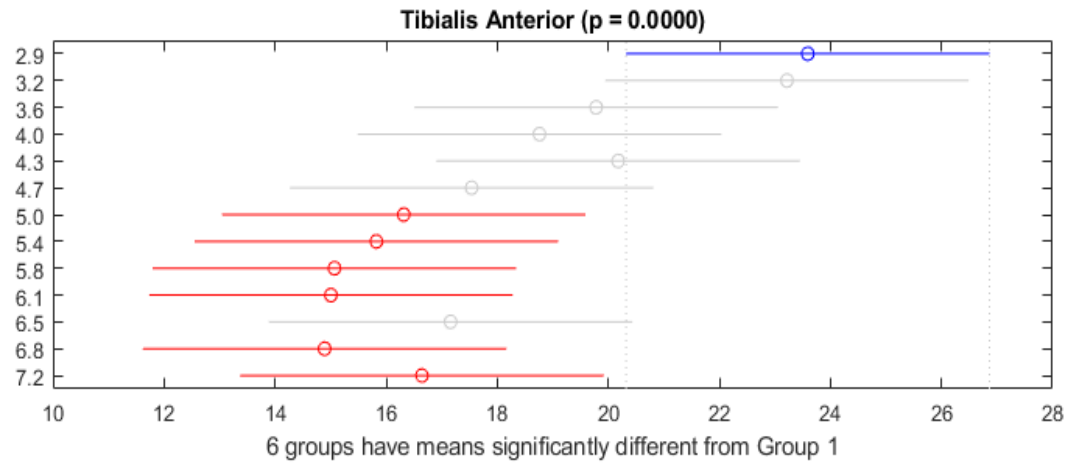


Figure 31. Post-hoc comparison of Tibialis Anterior muscle across walking speeds based on RMS feature: Group 2.9 km/h shows statistically significant differences with groups 5.0, 5.4, 5.8, 6.1, 6.8, and 7.2 km/h ($p < 0.05$).

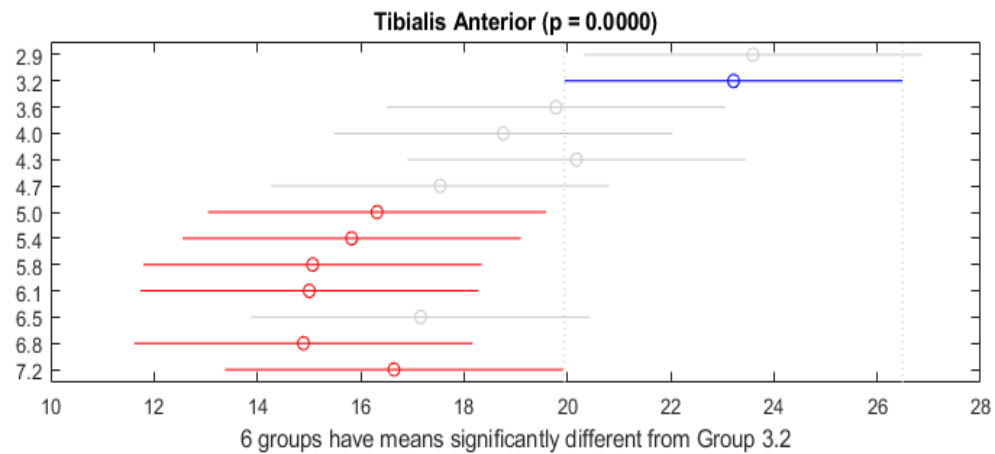


Figure 32. Post-hoc comparison of Tibialis Anterior muscle based on RMS feature: Group 3.2 km/h shows statistically significant differences with groups 5.0, 5.4, 5.8, 6.1, 6.8, and 7.2 km/h ($p < 0.05$).

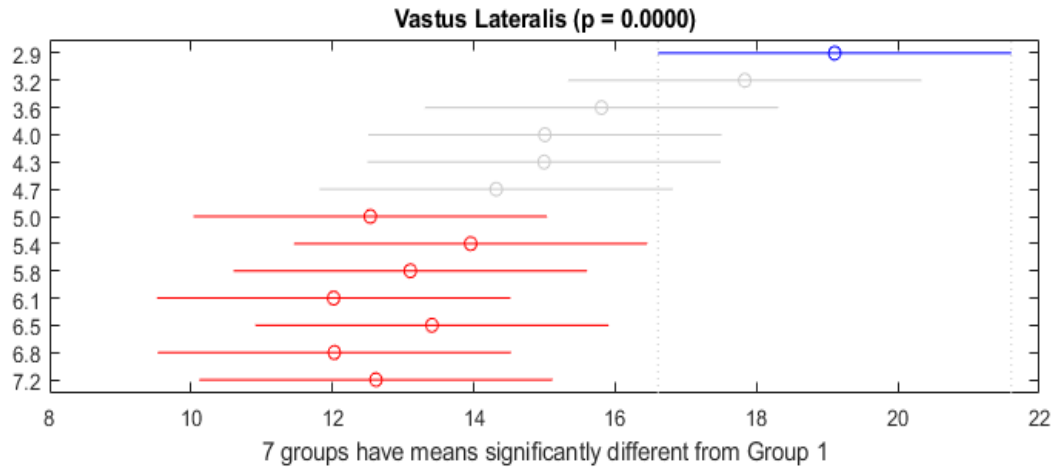


Figure 33. Post-hoc comparison of Vastus Lateralis muscle based on RMS feature: Group 2.9 km/h shows a statistically significant difference with group 5.0, 5.4, 5.8, 6.1, 6.5, 6.8, and 7.2 km/h ($p < 0.05$).

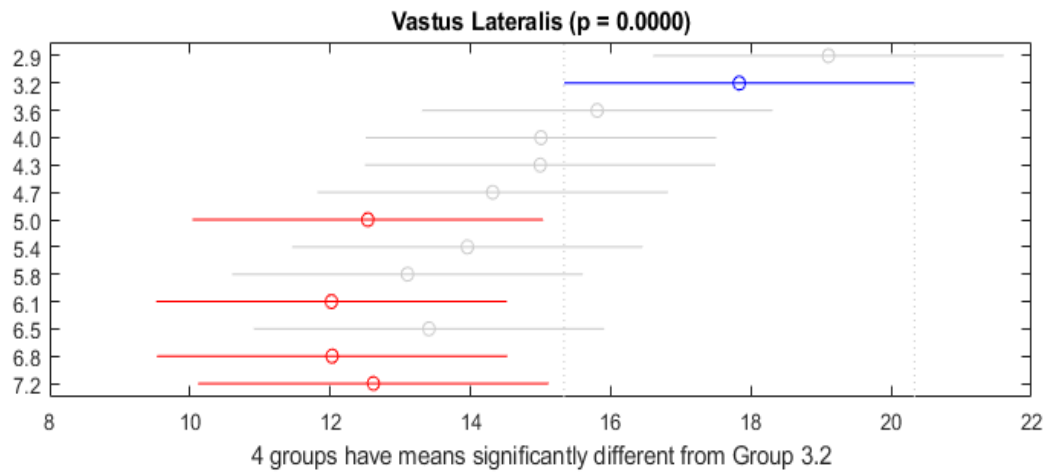


Figure 34. Post-hoc comparison of Vastus Lateralis muscle based on RMS feature: Group 3.2 km/h shows a statistically significant difference with group 5.0, 6.1, 6.8, and 7.2 km/h ($p < 0.05$).

Post hoc analysis results in the Tibialis Anterior muscle revealed that 2.9 km/h walking speed showed significantly higher symmetry index values compared to higher speeds such as 5.0, 5.4, 5.8, 6.1, 6.8 and 7.2 km/h. Similarly, 3.2 km/h speed also showed statistically significant differences in some comparisons with speeds of 5.0 km/h and above (Table 10). However, no statistically significant differences were detected in comparisons made between medium and high speeds other than 2.9 and 3.2 km/h (e.g. 3.6, 4.0, 4.3, 4.7 km/h and above) ($p > 0.05$).

Table 10

Symmetry Index Differences Across Walking Speeds for Tibialis Anterior Muscle – Post Hoc Results (RMS Feature, Speed: km/h)

Speed 1	Speed 2	Estimate	LowerCI	UpperCI	pValue
2.9	5.0	7.28	0.73	13.82	0.014
2.9	5.4	7.77	1.22	14.31	0.006
2.9	5.8	8.52	1.98	15.07	0.001
2.9	6.1	8.59	2.04	15.13	0.001
2.9	6.8	8.70	2.15	15.25	0.001
2.9	7.2	6.95	0.40	13.49	0.026
3.2	5.0	6.90	0.35	13.45	0.028
3.2	5.4	7.39	0.85	13.94	0.012
3.2	5.8	8.15	1.60	14.69	0.003
3.2	6.1	8.21	1.67	14.76	0.002
3.2	6.8	8.33	1.78	14.87	0.002
3.2	7.2	6.57	0.03	13.12	0.048

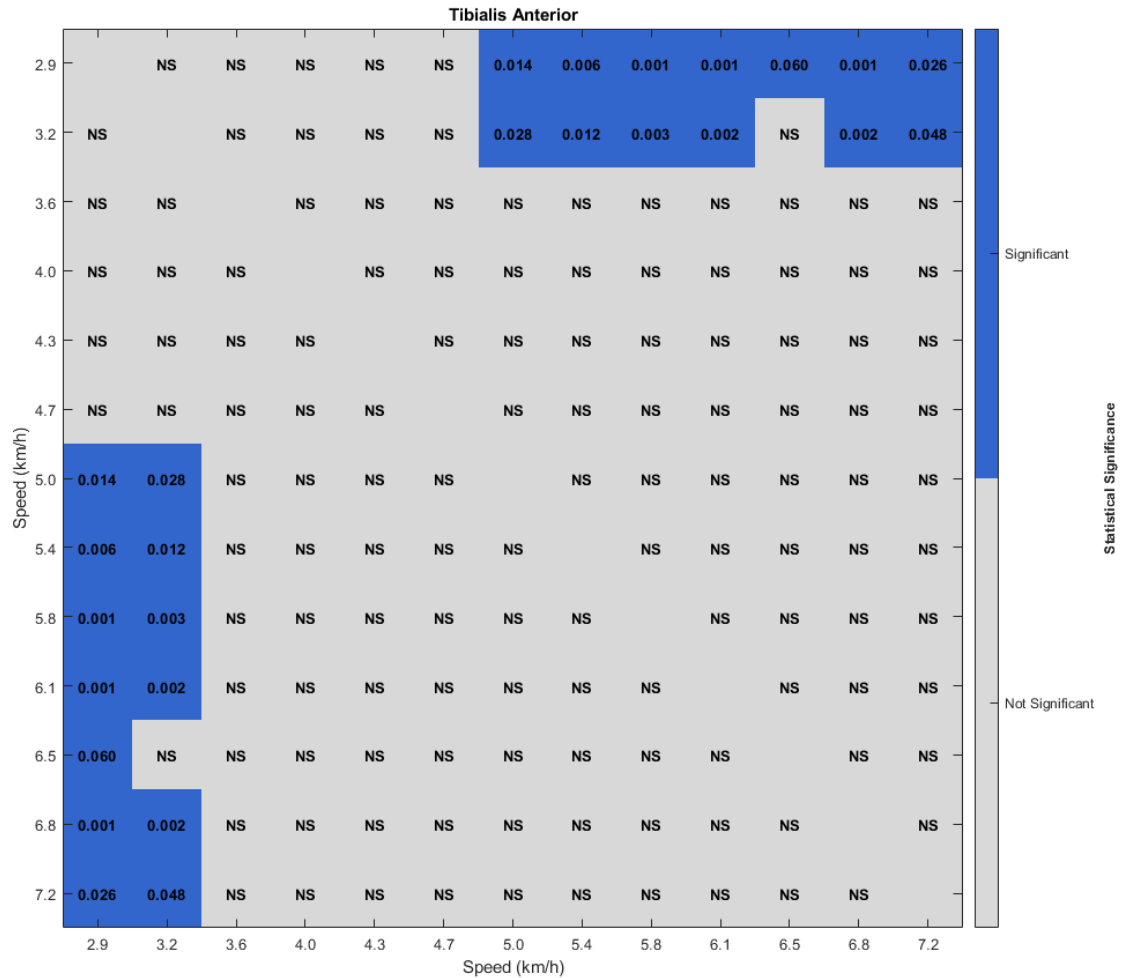


Figure 35. Post-hoc pairwise statistical significance matrix of symmetry index for Tibialis Anterior – RMS feature analysis

* To evaluate the differences in symmetry index between walking speeds more sensitively, $p < 0.1$ level was preferred.

As a result of post-hoc comparisons between walking speeds for the GM muscle, no statistically significant symmetry index difference was observed between any speed pair ($p > 0.05$).

As a result of post-hoc comparison analysis for the Vastus Lateralis muscle, significant differences were detected especially between the low walking speeds of 2.9 km/h and 3.2 km/h and higher speeds. The 2.9 km/h speed showed significantly higher symmetry index values compared to the speeds of 5.0, 5.4, 5.8, 6.1, 6.5, 6.8 and 7.2 km/h.

Similarly, the 3.2 km/h speed also presented significant differences in comparisons made with the speeds of 5.0, 6.1, 6.8 and 7.2 km/h (Table 11). On the other hand, no statistically significant difference was found in the comparisons between the medium speeds of 3.6, 4.0, 4.3 and 4.7 km/h and the other speeds ($p > 0.05$).

Table 11

Symmetry Index Differences Across Walking Speeds for Vastus Lateralis Muscle – Post Hoc Results (RMS Feature, Speed: km/h)

Speed 1	Speed 2	Estimate	LowerCI	UpperCI	pValue
2.9	5.0	6.57	1.57	11.57	0.0009
2.9	5.4	5.15	0.15	10.15	0.0363
2.9	5.8	6.00	1.00	11.00	0.0047
2.9	6.1	7.09	2.09	12.08	0.0002
2.9	6.5	5.70	0.70	10.69	0.0102
2.9	6.8	7.08	2.08	12.08	0.0002
2.9	7.2	6.49	1.49	11.49	0.0012
3.2	5.0	5.30	0.30	10.30	0.0263
3.2	6.1	5.82	0.82	10.81	0.0076
3.2	6.8	5.81	0.81	10.80	0.0078
3.2	7.2	5.22	0.22	10.22	0.0314

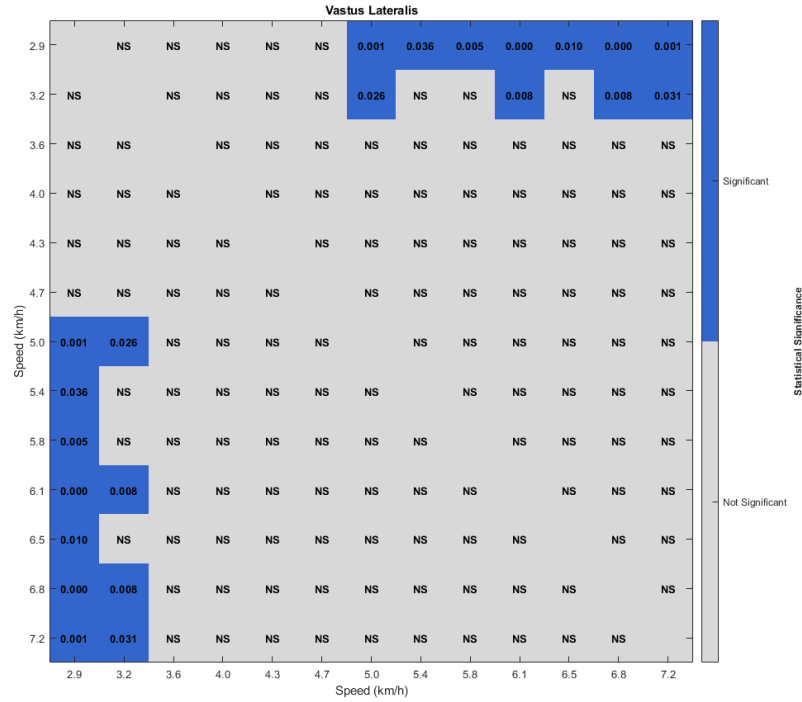


Figure 36. Post-hoc pairwise statistical significance matrix of symmetry index for Vastus Lateralis – RMS feature analysis

4.3 Frame-Based Symmetry Analysis Across Waking Speeds

SI and Standard Deviation: The distribution of SI and Std values of five muscle groups (Tibialis Anterior, Gastrocnemius Medialis, Soleus, Vastus Lateralis and Biceps Femoris) at different walking speeds is presented numerically in Table 12 and visually in Figures 37–41.

Table 12

Mean and Standard Deviation (Mean $\pm$ SD) of Symmetry Index Values in Each Muscle at Different Walking Speeds -Frame Based

	TA	GAS	SOL	VL	BF
2.9 km/h	45.87 $\pm$ 8.33	53.81 $\pm$ 7.76	38.56 $\pm$ 4.68	50.14 $\pm$ 6.82	39.44 $\pm$ 6.95
3.2 km/h	43.34 $\pm$ 8.23	51.28 $\pm$ 5.08	38.10 $\pm$ 4.85	49.06 $\pm$ 6.53	39.22 $\pm$ 7.85
3.6 km/h	40.33 $\pm$ 7.56	48.95 $\pm$ 5.12	36.19 $\pm$ 4.51	45.90 $\pm$ 5.53	38.30 $\pm$ 8.45
4.0 km/h	39.75 $\pm$ 5.75	47.24 $\pm$ 6.29	35.74 $\pm$ 4.20	43.89 $\pm$ 4.92	41.12 $\pm$ 18.94
4.3 km/h	41.71 $\pm$ 8.05	45.51 $\pm$ 5.89	35.10 $\pm$ 3.82	42.27 $\pm$ 3.72	38.97 $\pm$ 10.43

Table 12 (cont'd)

4.7 km/h	39.03 ± 6.88	44.92 ± 4.82	35.19 ± 4.90	40.93 ± 3.76	33.69 ± 5.02
5.0 km/h	38.29 ± 5.60	42.83 ± 5.00	33.78 ± 3.89	39.85 ± 4.98	36.89 ± 7.20
5.4 km/h	38.50 ± 5.01	41.99 ± 4.52	33.07 ± 3.44	39.12 ± 3.58	36.51 ± 6.97
5.8 km/h	37.80 ± 5.88	42.44 ± 5.89	32.25 ± 3.97	37.89 ± 3.63	35.59 ± 3.93
6.1 km/h	37.92 ± 5.65	41.83 ± 4.80	32.00 ± 4.20	37.25 ± 3.29	36.96 ± 6.62
6.5 km/h	38.37 ± 6.84	41.58 ± 5.70	32.25 ± 3.30	37.25 ± 2.47	39.20 ± 7.79
6.8 km/h	38.69 ± 4.63	42.25 ± 8.25	32.35 ± 3.49	37.05 ± 3.02	37.22 ± 5.25
7.2 km/h	40.49 ± 6.52	42.56 ± 5.45	32.54 ± 3.20	37.25 ± 2.68	38.57 ± 6.65

The Tibialis Anterior muscle was observed as $45.87 \pm 8.33\%$ at 2.9 km/h. These values decreased as the walking speed increased and decreased to $38.29 \pm 5.60\%$ at 5.0 km/h and then stabilized at a certain level.

The Gastrocnemius Medialis muscle also showed a similar trend. The symmetry index value, which was $53.81 \pm 7.76\%$ at 2.9 km/h, decreased to $42.83 \pm 5.00\%$ at 5.0 km/h.

The soleus muscle attracted attention as a muscle with similar symmetry index values. The value, which was $38.56 \pm 4.68\%$ at 2.9 km/h, gradually decreased up to 7.2 km/h and decreased to $32.54 \pm 3.20\%$.

Vastus Lateralis muscle also had a high symmetry index at low speeds ($50.14\% \pm 6.82$), but showed a significant decrease as speed increased and decreased to $37.25\% \pm 2.68$ at 7.2 km/h.

Fluctuations were observed in the symmetry index values for Biceps Femoris muscle. Especially the high standard deviation value at 4.0 km/h ($41.12\% \pm 18.94$) is seen.

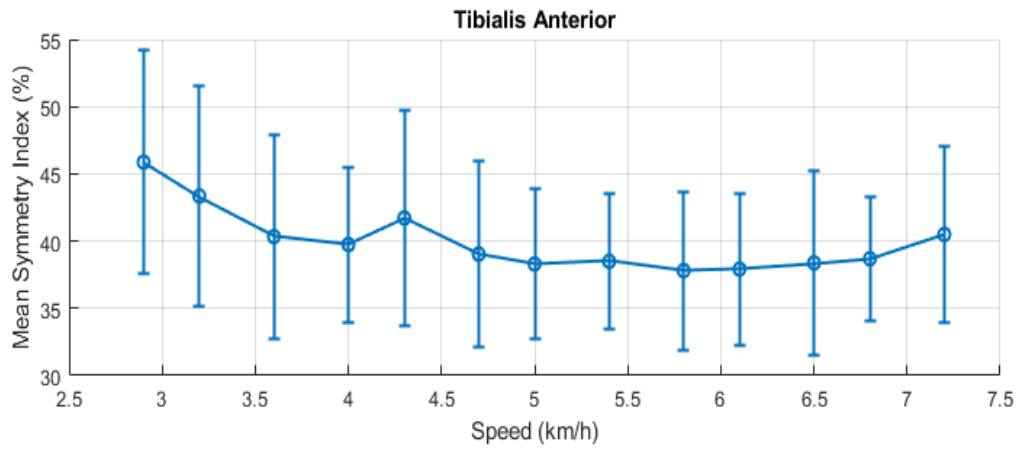


Figure 37. Frame-Based Symmetry Index Distribution in the Tibialis Anterior Muscle Across Walking Speeds.

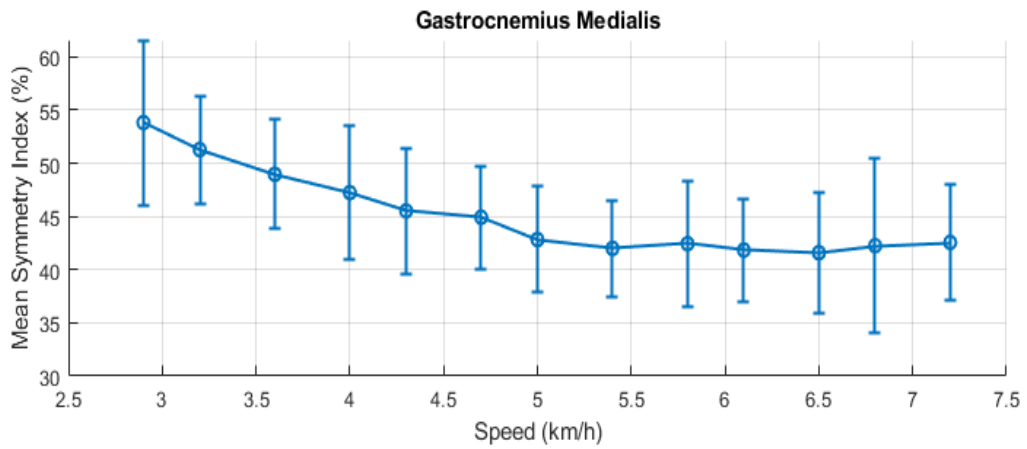


Figure 38. Frame-Based Symmetry Index Distribution in the Gastrocnemius Medialis Muscle Across Walking Speeds.

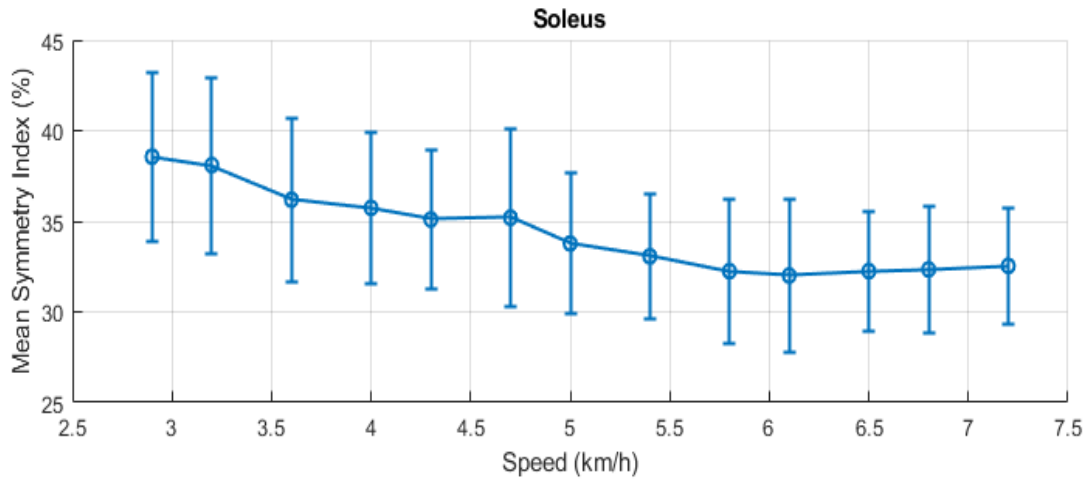


Figure 39. Frame-Based Symmetry Index Distribution in the Soleus Muscle Across Walking Speeds.

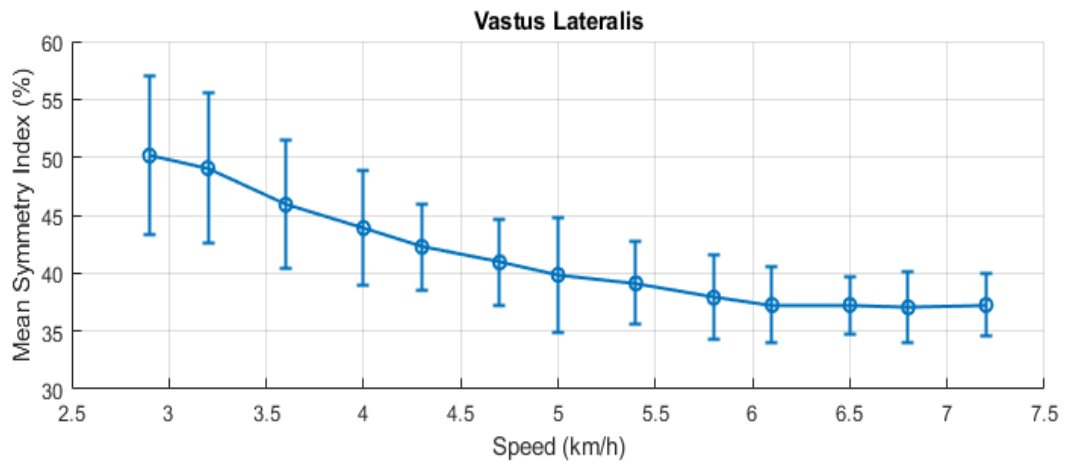


Figure 40. Frame-Based Symmetry Index Distribution in the Vastus Lateralis Muscle Across Walking Speeds.

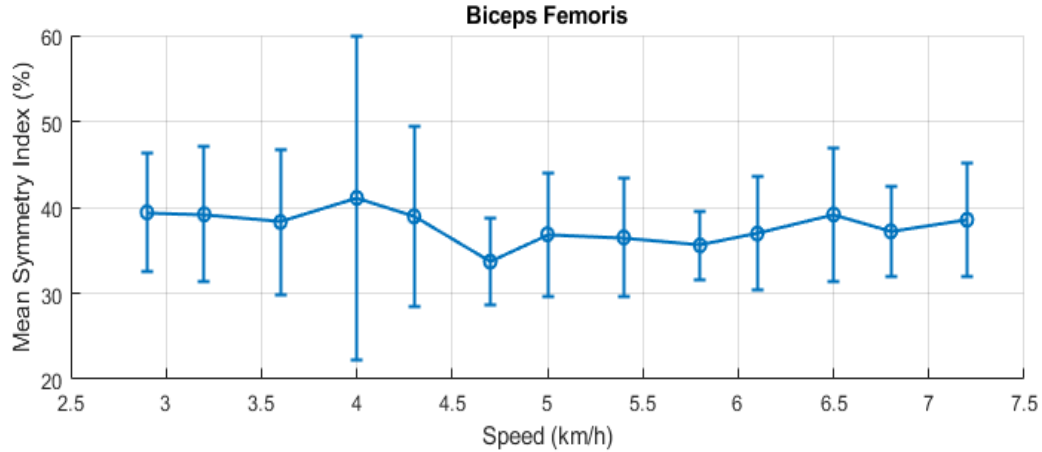


Figure 41. Frame-Based Symmetry Index Distribution in the Biceps Femoris Muscle Across Walking Speeds.

ANOVA Results: According to the one-way ANOVA analysis results, there were significant differences in terms of symmetry index between the walking speed groups in the Gastrocnemius Medialis ($p = 0.0000$), Soleus ($p = 0.0001$) and Vastus Lateralis ($p = 0.0000$) muscles, while no significant difference was found in the Tibialis Anterior ($p = 0.1110$) and Biceps Femoris ($p = 0.8331$) muscles.

The findings of the Tukey-Kramer post hoc test applied for the muscles with statistically significant differences because of the one-way ANOVA analysis are presented visually in Figures 42, 43, 45, 46, 48, 49, 50, and 51. Also, numerically in Tables 12–14 to show the significant differences between the relevant speed groups. These differences are also illustrated as heatmaps in Figures 44, 47 and 52.

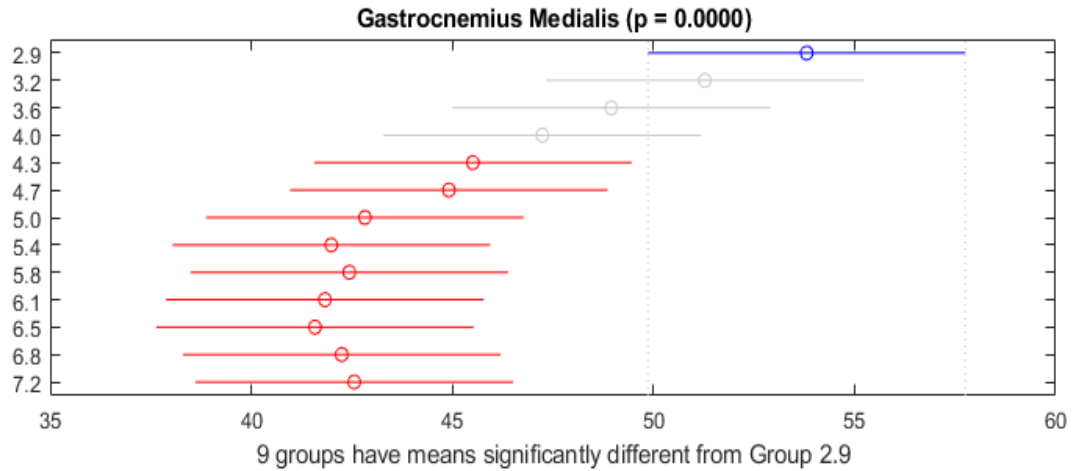


Figure 42. Post-hoc comparison of Gastrocnemius Medialis muscle in frame-based analysis: Nine walking speeds showed statistically significant difference from 2.9 km/h ($p < 0.05$).

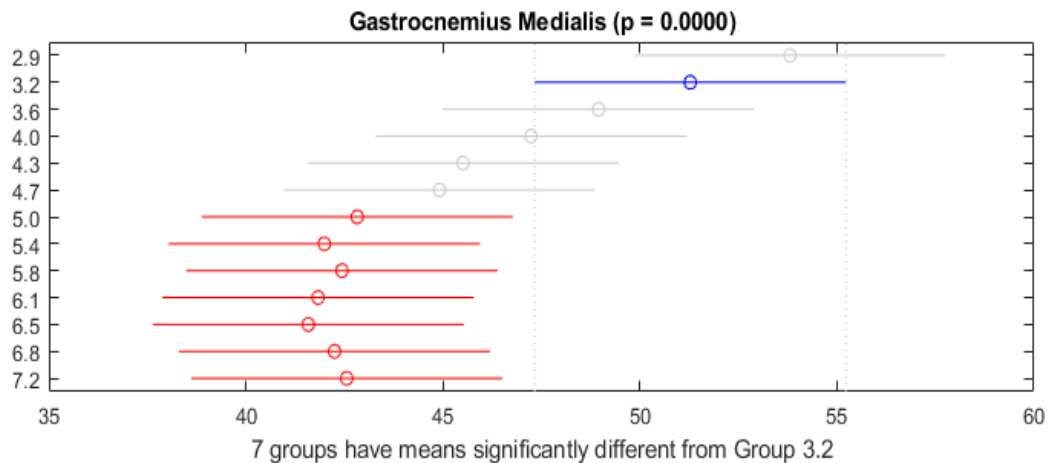


Figure 43. Post-hoc comparison of Gastrocnemius Medialis muscle in frame-based analysis: Seven walking speeds showed a statistically significant difference from 3.2 km/h ($p < 0.05$).

Post hoc comparison results of GM muscle revealed that individuals walking at 2.9 km/h had significantly higher symmetry index values compared to individuals walking at speeds of 4.3 km/h and above ($p < 0.05$). Especially, 2.9 km/h speed showed significantly higher mean differences when compared to speeds of 5.0, 5.4, 5.8, 6.1, 6.5, 6.8 and 7.2 km/h. Similarly, individuals walking at 3.2 km/h had significantly higher

symmetry index when compared to speeds of 5.0 km/h and above. This difference was statistically significant especially at speeds of 5.4, 6.1 and 6.5 km/h ($p < 0.05$) (Table 13).

Table 13

Symmetry Index Differences Across Walking Speeds for the Gastrocnemius Medialis Muscle – Post Hoc Results (Frame-based, Speed: km/h)

Speed 1	Speed 2	Estimate	LowerCI	UpperCI	pValue
2.9	4.3	8.30	0.40	16.19	0.029
2.9	4.7	8.89	1.00	16.79	0.012
2.9	5.0	10.98	3.09	18.88	$p < 0.001$
2.9	5.4	11.82	3.92	19.71	$p < 0.001$
2.9	5.8	11.37	3.48	19.27	$p < 0.001$
2.9	6.1	11.98	4.08	19.87	$p < 0.001$
2.9	6.5	12.22	4.33	20.12	$p < 0.001$
2.9	6.8	11.56	3.66	19.46	$p < 0.001$
2.9	7.2	11.25	3.35	19.14	$p < 0.001$
3.2	5.0	8.45	0.56	16.35	0.023
3.2	5.4	9.29	1.39	17.18	0.0064
3.2	5.8	8.84	0.94	16.74	0.0131
3.2	6.1	9.45	1.55	17.34	0.0049
3.2	6.5	9.69	1.80	17.59	0.0033
3.2	6.8	9.03	1.13	16.92	0.0097
3.2	7.2	8.72	0.82	16.61	0.0157

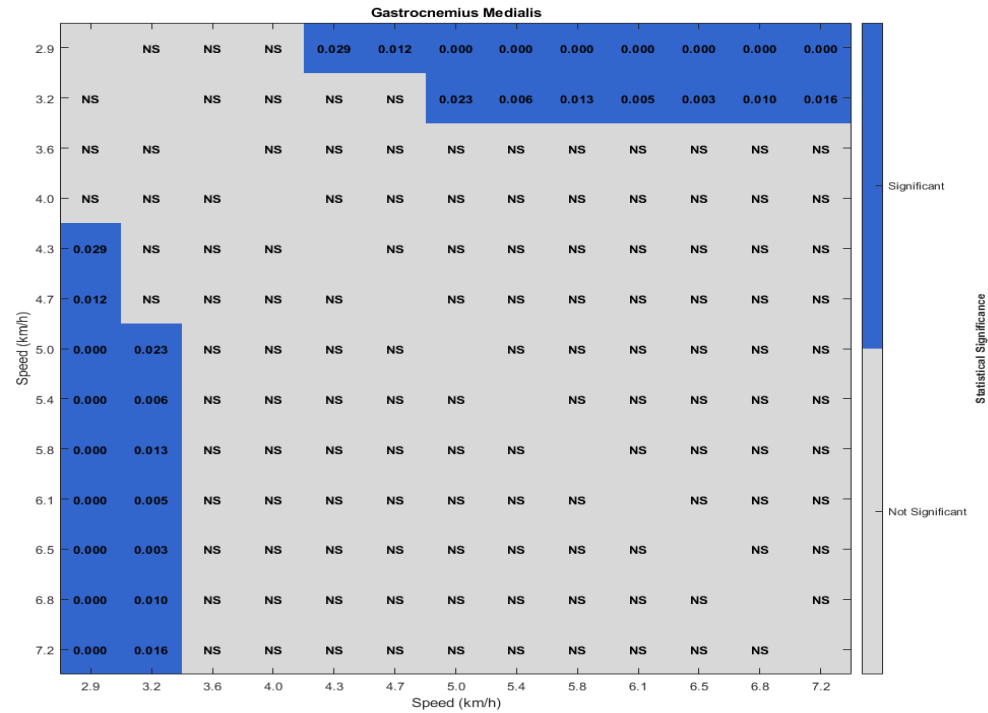


Figure 44. Post-hoc pairwise statistical significance matrix of symmetry index for Gastrocnemius Medialis – Frame based analysis

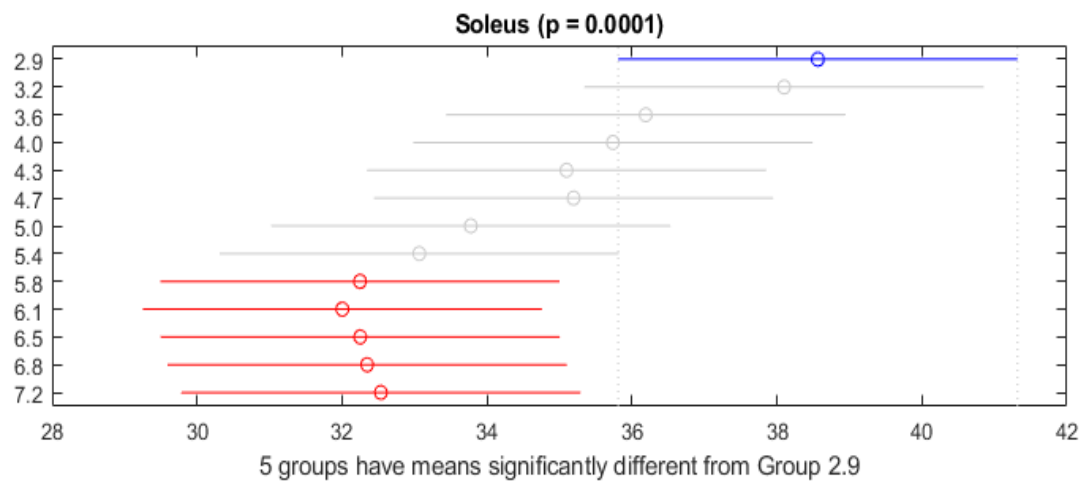


Figure 45. Post-hoc comparison of Soleus muscle in frame-based analysis: Five walking speeds showed a statistically significant difference from 2.9 km/h ($p < 0.05$).

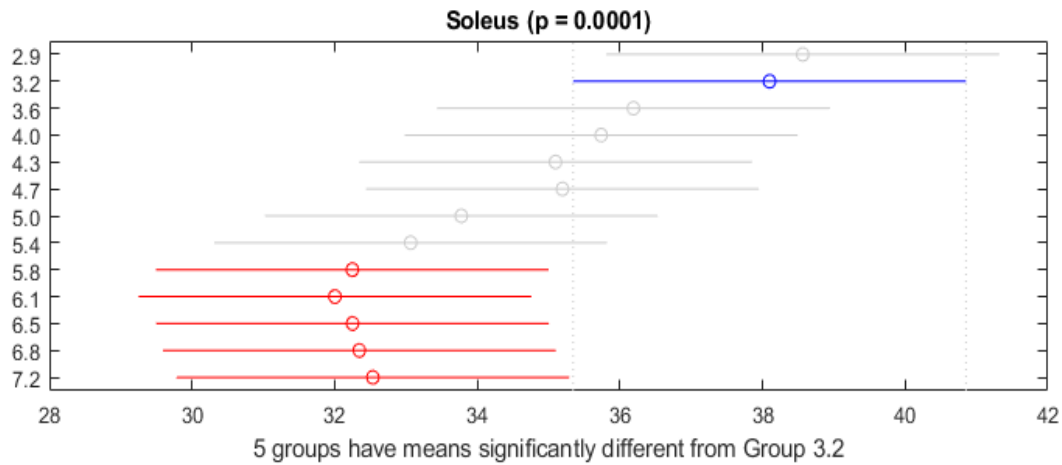


Figure 46. Post-hoc comparison of Soleus muscle in frame-based analysis: Five walking speeds showed a statistically significant difference from 3.2 km/h ($p < 0.05$).

Post hoc comparison results of SOL muscle showed that individuals walking at 2.9 km/h had significantly higher symmetry index values compared to individuals walking at speeds of 5.8, 6.1, 6.5, 6.8 and 7.2 km/h ($p < 0.05$). The difference was more pronounced especially in comparison with speed of 6.1 km/h ($p = 0.0053$). Similarly, individuals walking at speeds of 3.2 km/h had a significantly higher symmetry index compared to individuals walking at speeds of 5.8 km/h and above ($p < 0.05$). The difference was more significant in comparison of 3.2 km/h and 6.1 km/h ($p = 0.0153$) (Table 14).

Table 14

Symmetry Index Differences Across Walking Speeds for the Soleus Muscle – Post Hoc Results (Frame-based, Speed: km/h)

Speed 1	Speed 2	Estimate	LowerCI	UpperCI	pValue
2.9	5.8	6.32	0.81	11.82	0.0093
2.9	6.1	6.56	1.05	12.07	0.0053
2.9	6.5	6.31	0.81	11.82	0.0094
2.9	6.8	6.22	0.71	11.73	0.0117
2.9	7.2	6.03	0.52	11.54	0.0176
3.2	5.8	5.85	0.34	11.36	0.0255
3.2	6.1	6.09	0.59	11.60	0.0153

Table 14 (cont'd)

3.2	6.5	5.85	0.34	11.36	0.0256
3.2	6.8	5.75	0.24	11.26	0.0311
3.2	7.2	5.56	0.06	11.07	0.0450

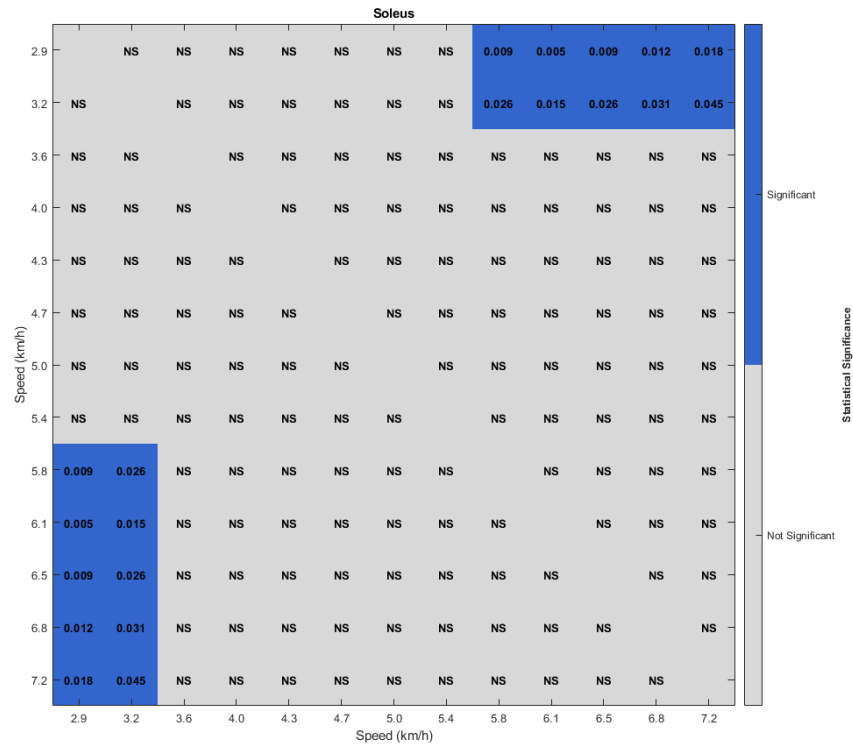


Figure 47. Post-hoc pairwise statistical significance matrix of symmetry index for

Soleus – Frame based analysis

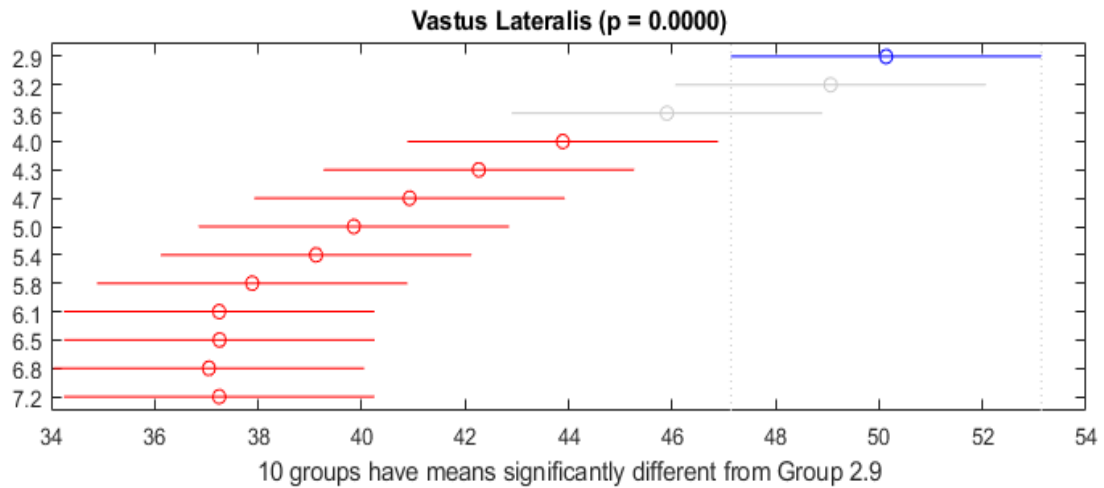


Figure 48. Post-hoc comparison of Vastus Lateralis muscle in frame-based analysis: Ten walking speeds showed a statistically significant difference from 2.9 km/h ($p < 0.05$).

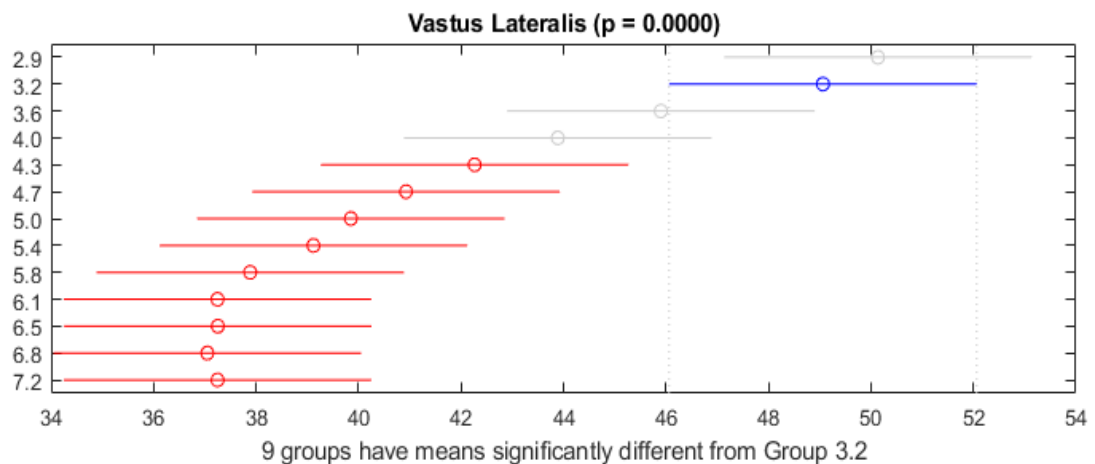


Figure 49. Post-hoc comparison of Vastus Lateralis muscle in frame-based analysis: Nine walking speeds showed a statistically significant difference from 3.2 km/h ($p < 0.05$).

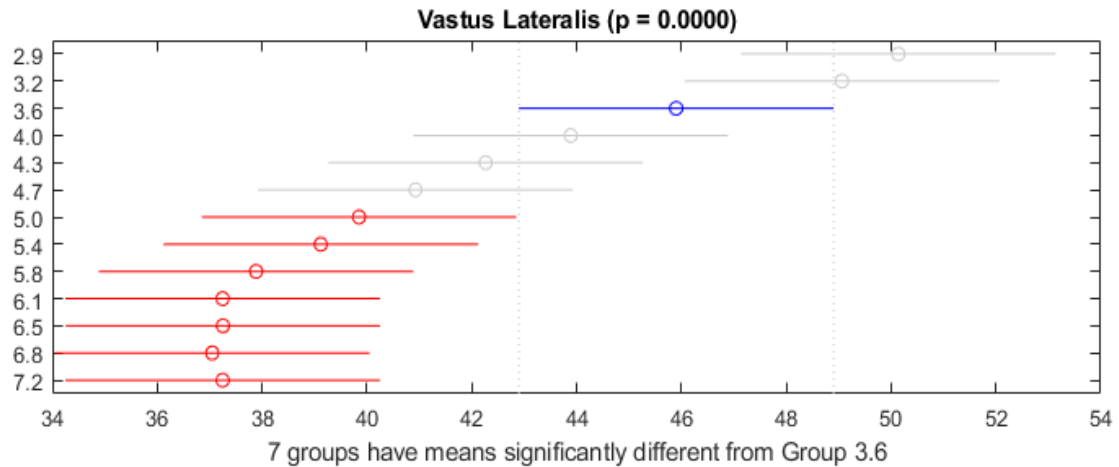


Figure 50. Post-hoc comparison of Vastus Lateralis muscle in frame-based analysis: Seven walking speeds showed a statistically significant difference from 3.6 km/h ($p < 0.05$).

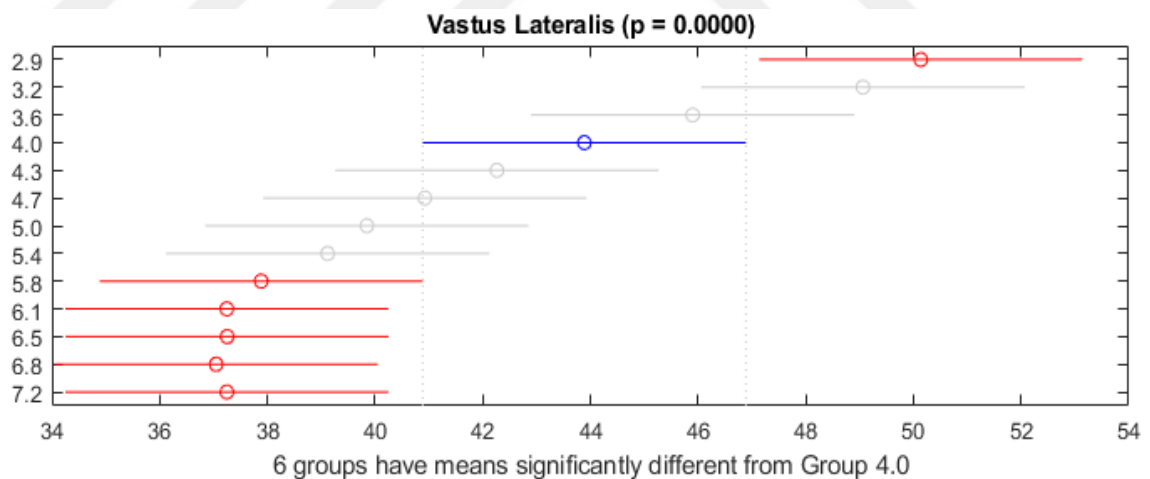


Figure 51. Post-hoc comparison of Vastus Lateralis muscle in frame-based analysis: Six walking speeds showed a statistically significant difference from 4.0 km/h ($p < 0.05$).

In the post hoc comparison of the vastus lateralis muscle, 2.9 km/h walking speed showed a significant difference in all speeds from 4.0 to 7.2 km/h ($p < 0.05$). Similarly, 3.2 km/h walking speed also showed a statistically significant difference in all speeds from 4.3 to 7.2 km/h ($p < 0.05$). 3.6 km/h speed showed a significant difference in all speeds

from 5.0 to 7.2 km/h. It is noteworthy that these differences were pronounced at 6.1 km/h ($p < 0.001$) and 6.8 km/h ($p < 0.001$). Additionally, 4.0 km/h walking speed had significantly higher symmetry index values compared to 5.8, 6.1, 6.5, 6.8 and 7.2 km/h speeds ($p < 0.05$) (Table 15).

Table 15

Symmetry Index Differences Across Walking Speeds for the Vastus Lateralis Muscle – Post Hoc Results (Speed: km/h)

Speed 1	Speed 2	Estimate	LowerCI	UpperCI	pValue
2.9	4.0	6.25	0.25	12.25	0.032
2.9	4.3	7.87	1.87	13.87	$p < 0.001$
2.9	4.7	9.21	3.21	15.21	$p < 0.001$
2.9	5.0	10.29	4.29	16.29	$p < 0.001$
2.9	5.4	11.02	5.02	17.02	$p < 0.001$
2.9	5.8	12.25	6.25	18.25	$p < 0.001$
2.9	6.1	12.89	6.89	18.89	$p < 0.001$
2.9	6.5	12.88	6.88	18.89	$p < 0.001$
2.9	6.8	13.09	7.09	19.09	$p < 0.001$
2.9	7.2	12.89	6.89	18.89	$p < 0.001$
3.2	4.3	6.80	0.80	12.80	0.011
3.2	4.7	8.14	2.14	14.14	$p < 0.001$
3.2	5.0	9.21	3.21	15.21	$p < 0.001$
3.2	5.4	9.94	3.94	15.94	$p < 0.001$
3.2	5.8	11.18	5.18	17.18	$p < 0.001$
3.2	6.1	11.81	5.81	17.82	$p < 0.001$
3.2	6.5	11.81	5.81	17.81	$p < 0.001$

Table 15 (cont'd)

3.2	6.8	12.01	6.01	18.01	$p < 0.001$
3.2	7.2	11.81	5.81	17.81	$p < 0.001$
3.6	5.0	6.05	0.05	12.05	0.0459
3.6	5.4	6.78	0.78	12.78	0.0115
3.6	5.8	8.02	2.01	14.02	$p < 0.001$
3.6	6.1	8.65	2.65	14.65	$p < 0.001$
3.6	6.5	8.65	2.65	14.65	$p < 0.001$
3.6	6.8	8.85	2.85	14.85	$p < 0.001$
3.6	7.2	8.65	2.65	14.65	$p < 0.001$
4.0	5.8	6.00	0.00	12.00	0.04995
4.0	6.1	6.64	0.64	12.64	0.0153
4.0	6.5	6.63	0.63	12.64	0.0155
4.0	6.8	6.84	0.84	12.84	0.0102
4.0	7.2	6.64	0.64	12.64	0.0153

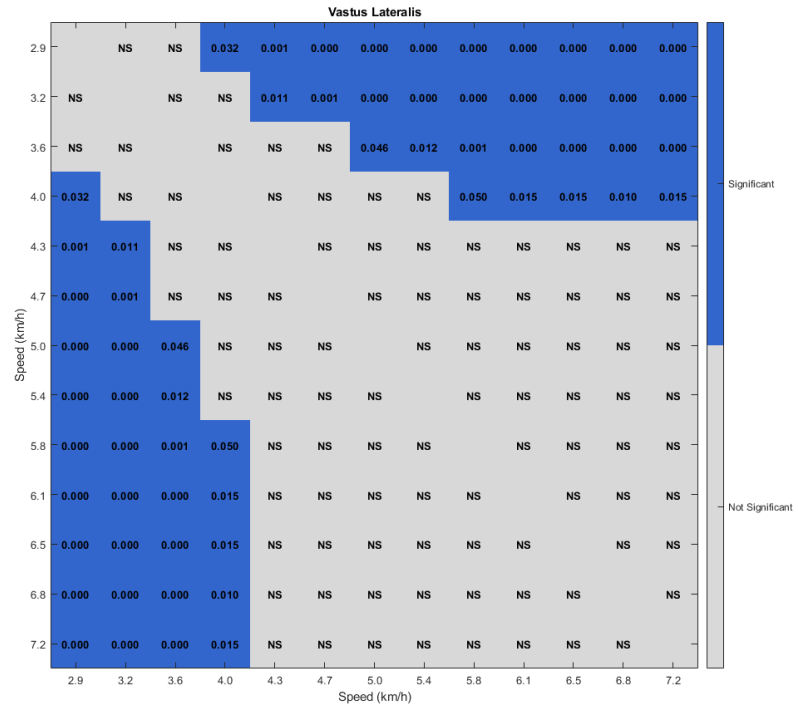


Figure 52. Post-hoc pairwise statistical significance matrix of symmetry index for Vastus Lateralis – Frame based analysis

4.4 Correlation Between Speed and Symmetry Index

The correlation results between the speed and symmetry index obtained via the MAV feature are given in Table 16 on a muscle basis. The correlation coefficient (r), significance level (p) and explanation made according to the Dancey & Reidy scale are included in the table, and the graphical representation of these results is presented in Figure 53.

Table 16

Correlation Results Between Walking Speed and Symmetry Index Based on MAV

Feature

Muscle	r	p	Explanation
Tibialis Anterior	-0.369	0.0000	Moderate negative and significant.
Gastrocnemius Medialis	-0.289	0.0003	Weak negative and significant.
Soleus	-0.329	0.0000	Weak negative and significant.
Vastus Lateralis	-0.478	0.0000	Moderate negative and significant.
Biceps Femoris	-0.137	0.0890	Not significant.

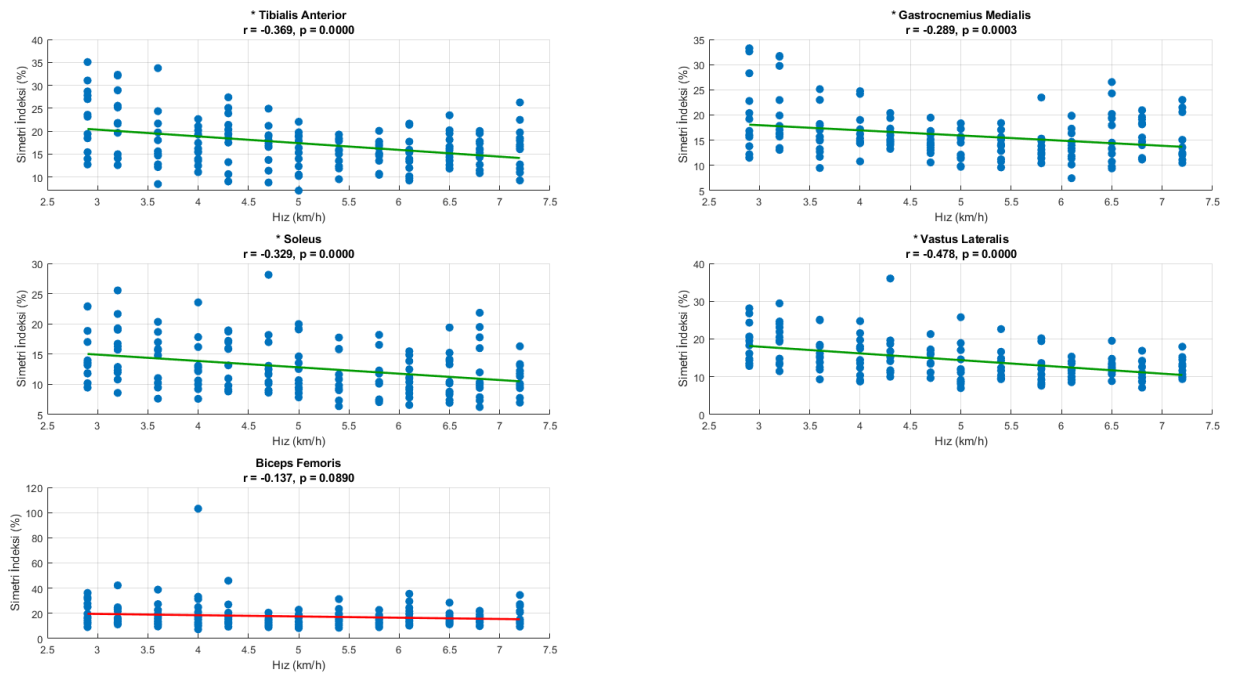


Figure 53. Correlation between walking speed and symmetry index based on MAV feature for each muscle.

The correlation results between the speed and symmetry index obtained from the AR feature are given in Table 17 on a muscle basis, and its graphical representation is presented in Figure 54.

Table 17

Correlation Results Between Walking Speed and Symmetry Index Based on AR Feature

Muscle	r	p	Explanation
Tibialis Anterior	-0.220	0.0057	Weak negative and significant
Gastrocnemius Medialis	-0.174	0.0296	Weak negative and significant
Soleus	-0.159	0.0476	Weak negative and significant
Vastus Lateralis	-0.139	0.0827	Weak negative and not significant
Biceps Femoris	-0.461	0.0000	Moderate negative and significant

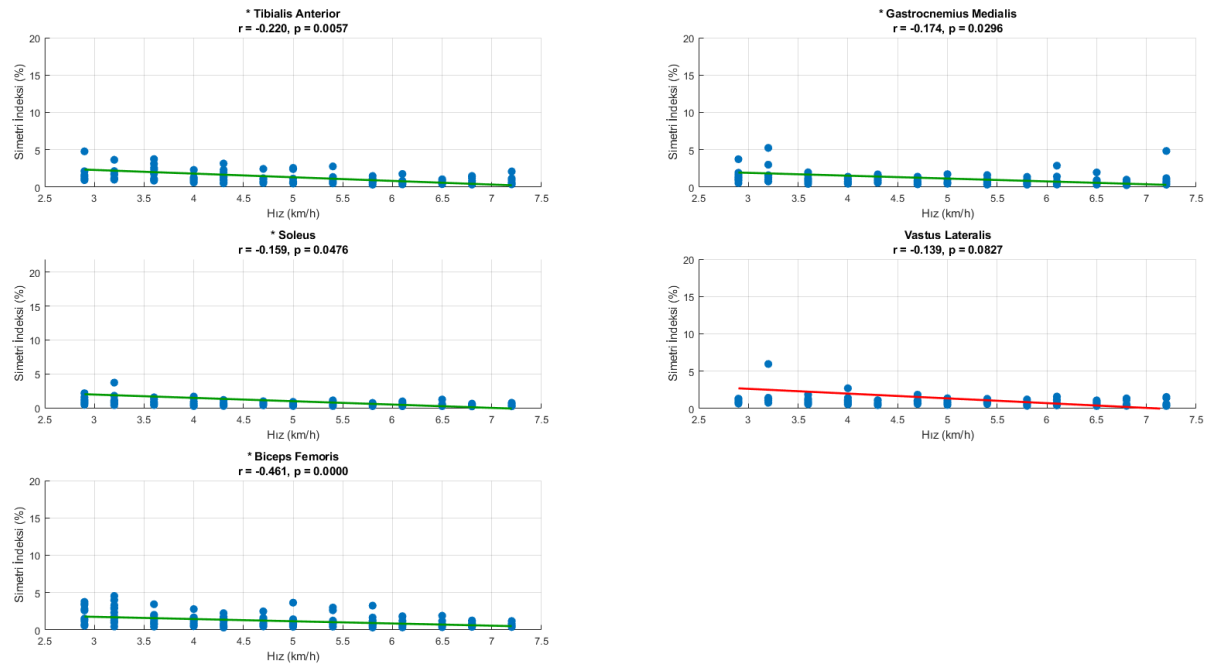


Figure 54. Correlation between walking speed and symmetry index based on AR feature for each muscle.

The correlation results between speed and symmetry index obtained via RMS feature are given in Table 18 on a muscle basis, and its graphical representation is presented in Figure 55.

Table 18

Correlation Results Between Walking Speed and Symmetry Index Based on RMS Feature

Muscle	r	p	Explanation
Tibialis Anterior	-0.443	0.0000	Moderate negative and significant
Gastrocnemius Medialis	-0.088	0.2740	Negligible, not significant
Soleus	-0.268	0.0007	Weak negative and significant
Vastus Lateralis	-0.452	0.0000	Moderate negative and significant
Biceps Femoris	-0.201	0.0118	Weak negative and significant

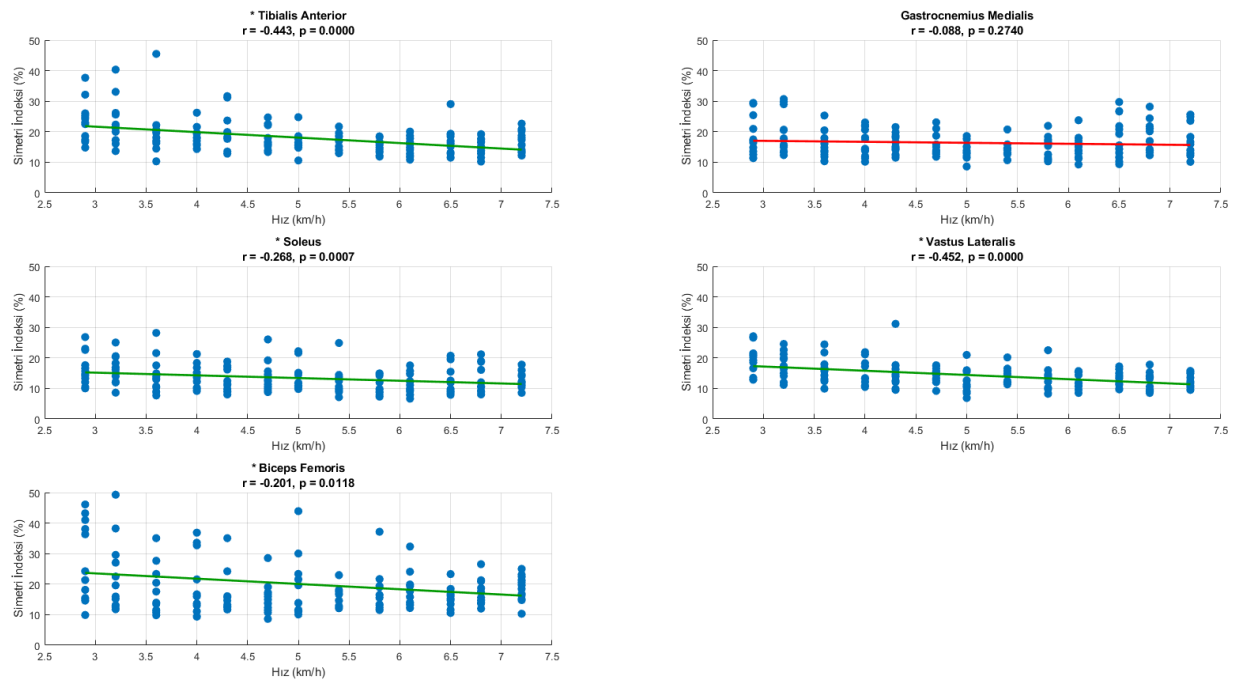


Figure 55. Correlation between walking speed and symmetry index based on RMS feature for each muscle.

The correlation results between speed and average symmetry index obtained via frame based examined data are given in Table 19 on a muscle basis, and its graphical representation is presented in Figure 56.

Table 19

Correlation Results Between Walking Speed and Symmetry Index Based on Frame

Muscle	r	p	Explanation
Tibialis Anterior	-0.236	0.0031	Weak negative and significant
Gastrocnemius Medialis	-0.507	0.0000	Moderate negative and significant
Soleus	-0.459	0.0000	Moderate negative and significant
Vastus Lateralis	-0.680	0.0000	Strong negative and significant
Biceps Femoris	-0.068	0.3994	Not significant

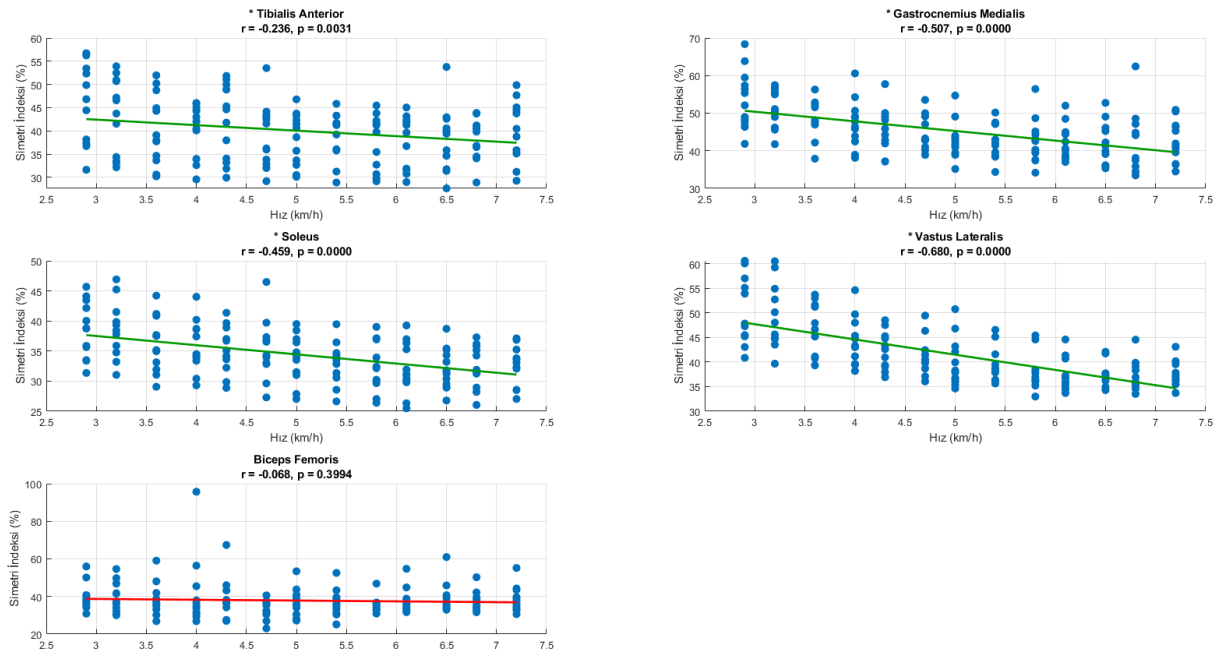


Figure 56. Correlation between walking speed and symmetry index for each muscle for frame-based

As a result of the correlation analysis, the relationships between the symmetry indices obtained with different EMG features (MAV, AR, RMS) and frame-based analysis methods and walking speed were examined. The results of each method differed on a muscle basis.

Particularly, frame-based analysis method found moderate and strong negative relationships in Vastus Lateralis ($r = -0.680$, $p < 0.001$), Gastrocnemius Medialis ($r = -0.507$, $p < 0.001$) and Soleus ($r = -0.459$, $p < 0.001$) muscles.

In the analysis based on different EMG features (MAV, AR and RMS), moderately significant negative correlations were found in the Tibialis Anterior ($r = -0.369$, $p < 0.001$) and Vastus Lateralis ($r = -0.478$, $p < 0.001$) muscles in the MAV-based analysis, while the correlation strength was weaker but still significant in the Gastrocnemius Medialis and Soleus muscles. This situation reveals that the MAV feature varies on a muscle basis in determining symmetry.

In AR-based analysis, generally weak and lower-level correlation coefficients were observed. Weak level but statistically significant negative correlations were detected for Tibialis Anterior ($r = -0.220$, $p = 0.0057$), Gastrocnemius Medialis ($r = -0.174$, $p = 0.0296$) and Soleus ($r = -0.159$, $p = 0.0476$) muscles. On the other hand, the correlation value obtained for Vastus Lateralis muscle was weak level but not statistically significant ($r = -0.139$, $p = 0.0827$). Biceps Femoris muscle, unlike the others, showed a moderate level negative and significant correlation ($r = -0.461$, $p < 0.001$).

In RMS (Root Mean Square) based analysis, significant negative correlations were observed between symmetry index and walking speed at different levels. Moderate negative and statistically significant correlations were found in Tibialis Anterior ($r = -0.443$, $p < 0.001$) and Vastus Lateralis ($r = -0.452$, $p < 0.001$) muscles. Weak negative and significant correlations were obtained in Soleus ($r = -0.268$, $p = 0.0007$) and Biceps Femoris ($r = -0.201$, $p = 0.0118$) muscles. On the other hand, the correlation value obtained for the Gastrocnemius Medialis muscle was negligible and not found to be statistically significant ($r = -0.088$, $p = 0.2740$).

Chapter 5

Discussion

5.1 Impact of Outlier Removal

A general decrease and a significant decrease in standard deviations were observed in the symmetry index analysis after outlier removal. For example, in the Tibialis Anterior muscle, the symmetry index decreased from 21.14% to 16.57% at 4.0 km/h, while the standard deviation decreased from 9.18 to 3.61, decreasing by approximately 60%. Similarly, in the Soleus muscle, the mean symmetry index decreased from 14.54% to 10.66% at 5.8 km/h, while the variance decreased by 68%. These results show that the removal of outliers significantly affected both the measure of central tendency and the variance.

More moderate changes were observed in muscles such as Gastrocnemius Medialis and Vastus Lateralis, indicating that some muscle groups were less affected by outliers.

Interestingly, both the mean symmetry index and standard deviation increased at 4.0 km/h in the Biceps Femoris muscle. This suggests that removing outliers does not always reduce variance, and that reducing the sample size at some speed and muscle combinations may cause an increase in variance in the opposite direction.

When evaluated in general, a more homogeneous and more reliable data structure in terms of analysis was obtained thanks to the outlier removal process. This increases the significance level of statistical tests, allowing for a more accurate interpretation of symmetry changes depending on walking speed.

5.2 Comparison of Gait Symmetry Analysis Findings - Feature and Frame Based

5.2.1 MAV feature analysis. MAV based symmetry analysis revealed that the symmetry index between muscles changed significantly at different walking speeds. It was observed that the symmetry indexes of TA, GM, SOL and VL muscles decreased significantly with increasing walking speed ($p < 0.05$). While the symmetry indexes were high especially at low speeds such as 2.9–3.2 km/h, lower and stable values were reached at speeds of 5.0 km/h and above.

These analysis shows that symmetry indices are higher at lower walking speeds, meaning more asymmetrical, whereas at higher speeds, the indices decrease, indicating increased symmetry. This suggests that low speeds in walking may create more imbalance and lack of muscle coordination. In this respect, the findings are like those of Bergamini et al. (2024), who reported that optimal symmetry was observed at moderate walking speeds (1.11–1.39 m/s), and that lower speeds were associated with greater asymmetry and Nasirzade et al. (2017) reported that the poorest symmetry was observed at slow speeds, and that the best symmetry occurred during fast walking.

The TA muscle has the highest symmetry indices at lower walking speeds (2.9-3.2 km/h), while these values decrease significantly at 5.0 km/h and above, showing a stable trend thereafter. Post hoc analysis also support this decrease statistically; it was found that speeds of 2.9 and 3.2 km/h had significantly higher symmetry indices than speeds of 5.0-6.8 km/h ($p < 0.05$). These findings indicate that increasing walking speed increases muscle synchronization and provides more symmetrical activation, especially in the TA muscle, as emphasized in the studies by Moreira et al. (2021) and Sousa & Tavares (2012).

A similar trend was observed in the GM muscle, with the symmetry index decreasing from $20.21 \pm 7.56\%$ at 2.9 km/h to $13.62 \pm 2.87\%$ at 5.0 km/h. Post hoc analysis revealed significant differences between 2.9 and 3.2 km/h and between 5.0 and 6.1 km/h ($p < 0.05$). These findings are consistent with the view reported by Sousa & Tavares (2012) that the activation of the GM muscle increases as walking speed increases, becoming more synchronous.

The SOL muscle had the lowest symmetry index values overall and this value decreased further as walking speed increased. This may reflect the SOL muscle working with a more natural and symmetric activation pattern during walking due to its contribution to postural balance. Although the difference between the groups was found significant in the ANOVA analysis ($p = 0.0329$), post hoc tests did not reveal any significant difference between specific speed pairs. This indicates that the symmetry difference between the individuals of the SOL muscle is low.

In the VL muscle, a high symmetry index was observed at low speeds (2.9-3.2 km/h), while these values decreased significantly at 5.0 km/h and beyond. Post hoc analysis revealed that this difference was statistically significant, indicating that the VL muscle entered a more synchronized working order as walking speed increased. These findings are parallel to the functional increase of the quadriceps group at high speeds, as described by Sousa & Tavares (2012) on the RF muscle.

Not significant difference was observed in the BF muscle statistically ($p = 0.2440$). However, the high variance at 4.0 km/h speed ($24.83 \pm 26.03\%$) indicates that there are significant differences between individuals in this muscle. This may suggest that it makes more of a difference because it is the closest speed to natural walking speed.

In general, MAV-based findings showed that symmetry index values generally decreased as speed increased and showed a more symmetrical gait. They also showed that symmetry improved in the TA, GM, and VL muscles with increasing speed; a naturally high level of symmetry was exhibited in the SOL muscle; and interindividual differences became prominent in the BF muscle. These findings are consistent with both the hypothesis and the functional asymmetry and EMG-based muscle activation patterns reported in the literature (Sousa & Tavares, 2012; Hof et al., 2002; Moreira et al., 2021).

5.2.2 AR feature analysis. AR-based symmetry analysis findings revealed varying symmetrical patterns among muscles at different walking speeds. While high symmetry index (SI) and standard deviation (SD) values were observed in all muscles, especially at low speeds such as 3.2 km/h, it was determined that these values significantly decreased and became stable at speeds of 6.1 km/h and above. This shows that low speeds are associated with more asymmetrical and interindividual variation, while a more stable and symmetrical gait occurs at high speeds. This general trend has also been reported in studies such as Nasirzade et al. (2017) and Bergamini et al. (2024).

In the TA muscle, the SI value reached a maximum level of 4.66 ± 10.32 at a speed of 3.2 km/h. While the SI was 1.57 ± 1.07 at 2.9 km/h, this value stabilized in the range of 0.68–0.74 with increasing speed. A similar trend was observed in the GM muscle. While the SI was 4.55 ± 10.27 at 3.2 km/h, this value decreased to 0.56–1.02 in the range of 6.8–7.2 km/h. Similarly, in the VL muscle, a very high variance of 7.91 ± 22.04 was found at a speed of 3.2 km/h, and the SI and SD values decreased as high speeds were reached. The SOL muscle showed a high variation with 5.44 ± 14.82 at 3.2 km/h and reached the most stable values at high speeds (SI: 0.41–0.46).

This decreasing trend observed in all these muscles indicates that a more symmetrical activation pattern occurs with increasing speed and motor control is better organized. However, these trends were not supported statistically. One-way ANOVA results did not reveal any significant differences ($p > 0.05$) in TA ($p = 0.0980$), VAS ($p = 0.1046$), SOL ($p = 0.2239$) and VL ($p = 0.2519$) muscles. Therefore, although there is a tendency for increasing symmetry with speed in these muscles, the statistical reliability of this difference is limited. This may be due to the high variations observed, especially at 3.2 km/h speed, since SI and SD values increase markedly at this speed.

In contrast, a statistically significant difference was found only in the BF muscle ($p = 0.0000$). Post hoc analysis revealed that there were significant differences, especially between low speeds (2.9 and 3.2 km/h) and high speeds (6.1 km/h and above). This shows that the BF muscle was significantly affected by speed. However, values such as SI: 2.28 ± 1.29 at 3.2 km/h and 0.99 ± 0.88 at 5.0 km/h indicate that there was a certain degree of

variation in the BF muscle. Therefore, in the BF muscle, the symmetry level appears to be influenced by both changes in walking speed and variations between individuals. In particular, the role of BF in different tasks such as hip extension and knee flexion may create changes in the activation pattern according to the walking strategies of individuals (Rice & Seeley, 2010).

In general, AR-based findings revealed an asymmetric structure associated with higher symmetry indices and variations at low speeds, and a structure characterized by lower and stable symmetry values at high speeds. A tendency for symmetry to increase with speed was observed in the TA, GM, SOL, and VL muscles, but these differences were not found to be statistically significant. In contrast, the BF muscle was significantly affected by speed and showed significant symmetry changes across walking speeds. These findings are consistent with the functional asymmetry and EMG-based muscle activation literature and overlap with the predictions of the hypothesis. In literature, studies such as Sousa & Tavares (2012), Hof et al. (2002), and Moreira et al. (2021) emphasize that changes in walking speed are directly related to muscle activation patterns and symmetry, and that some muscles can work more symmetrically, independent of speed.

5.2.3 RMS feature analysis. In the RMS (Root Mean Square) based symmetry analysis, significant differences were observed in the symmetry indices of the Tibialis Anterior (TA), Gastrocnemius Medialis (GM) and Vastus Lateralis (VL) muscles depending on the walking speed ($p = 0.0000$, $p = 0.0212$, $p = 0.0000$, respectively). The statistically significant differences were observed especially in the TA and VL muscles in the comparisons between low speeds (2.9–3.2 km/h) and high speeds (5.0–7.2 km/h), indicating that these muscles work more symmetrically as the speed increases and their activations become more synchronized. This finding is consistent with previous studies reporting speed-dependent changes in muscle activation. Moreira et al. (2021) showed that the Gastrocnemius Lateralis and Vastus Lateralis muscles exhibited increased activation at higher walking speeds. Similarly, Sousa & Tavares (2012) observed that muscle activation patterns varied with speed, with certain muscles like GM and RF showing greater activation during fast walking.

Hof et al. (2002) reported that the activation of the Tibialis Anterior muscle was primarily phase dependent rather than directly affected by walking speed. However, in the current study TA muscle decreased from 23.59 ± 6.56 at 2.9 km/h to 14.89 ± 2.59 at 6.8 km/h with the increase in walking speed, and this decrease was found to be statistically significant. This may indicate that the interlimb coordination of the TA muscle increases rapidly and becomes more symmetrical even if the activation itself is phase specific. A similar trend is observed in the VL muscle. While high symmetry indices were observed at low speeds (e.g. 19.10 ± 4.73 at 2.9 km/h), these values decreased to 12.03 ± 3.02 at 6.8 km/h. This shows that the quadriceps group started to work more efficiently and balanced with increasing speed. Sousa & Tavares (2012) emphasize that this muscle group shows optimization with speed.

A similar decreasing trend was observed in the GM muscle in general. However, post hoc analysis did not show significant differences between speed pairs. This may be due to the low variation and limited differences between groups. Hof et al. (2002) reported that the GM muscle showed an activation pattern that increased with speed but remained stable between certain speeds. The findings also support this trend.

There were no significant differences in the SOL and BF muscles depending on walking speed ($p = 0.546$ and $p = 0.3144$). However, the results indicate notable inter-individual differences in the BF muscle, particularly at the speeds of 2.9 and 4.0 km/h, as reflected by the considerably high standard deviation values (e.g., 26.96 ± 13.04 at 2.9 km/h and 26.10 ± 22.91 at 4.0 km/h). This shows that there are high inter-individual symmetry differences in the BF muscle. Motor control of dual-function muscles such as the BF (hip extension and knee flexion) may create more individual differences between walking strategies (Rice & Seeley, 2010). In addition, the fact that these differences appear especially at a speed of 4.0 km/h may be related to the fact that this speed is the transition point from comfortable walking to faster walking, where individuals can apply their own walking strategies more freely.

In the literature, RMS is considered as an indicator of muscle activation level, and it is stated that increased muscle effort can cause asymmetric structures with fatigue. Iwańska et al. (2021) emphasized that one leg showing more activation than the other with fatigue can disrupt symmetry. In this context, both the activation level and interindividual differences can affect symmetry in muscles that show high variance, such as BF.

As a result, a symmetrical activation increase with speed was clearly observed in the TA and VL muscles in the RMS-based analysis. Although a similar trend was found in the VAS muscle, these differences were not statistically detected. In the SOL and BF muscles, the effect of speed was limited, and interindividual differences were observed, especially in the BF. These findings show the effect of walking speed on muscle symmetry and that this effect is shaped by muscle-specific differences. The findings can be directly associated with concepts such as the effectiveness of motor control mechanisms defined in the literature (Hof et al., 2002), the effect of walking speed on muscle synchronization (Sousa & Tavares, 2012), and fatigue-induced symmetry disruptions (Iwańska et al., 2021).

5.2.4 Comparison between features and overall evaluation. When these features, MAV, AR and RMS, are evaluated together, it is clearly revealed that there is a muscle-specific difference between walking speed and muscle symmetry. While time-domain features such as MAV and RMS reveal symmetry differences more clearly statistically, modeling-based features such as AR represent individual variations better but are limited in comparisons between groups.

Since MAV analysis reflect the mean absolute value of muscle activity, they clearly showed an increase in symmetry as speed increased in TA, VAS and VL muscles. The AR approach, although finding a similar trend, was more limited in capturing significant differences across the group. RMS results, on the other hand, indicated a statistically significant improvement with speed increase in TA and VL muscles, while no significant change was detected in BF and Soleus (SOL) muscles. These findings show that the responses of muscles to speed changes depending on their anatomical and functional differences (Sousa & Tavares, 2012; Hof et al., 2002).

When the symmetry levels of individual muscles are examined, it is seen that the SOL muscle has the lowest SI values in general and exhibits a similar low-asymmetric (and therefore high-symmetric) activation at different speeds. This supports studies suggesting that the SOL is less affected by walking speed due to its postural support and “slow twitch” structure (Balius et al., 2012; Schmitz et al., 2009).

The BF muscle stood out with its high individual variance and showed large standard deviation values, although not statistically significant, at some speeds (e.g. 2.9 or 4.0 km/h). The double joint function of the BF may cause variation, but the high variation seen especially at 4 km/h, may be due to the fact that it is the closest to the natural walking speed. Therefore, unlike SOL, the BF muscle stands out as the muscle most affected by speed changes.

In other muscle groups, especially Tibialis Anterior (TA), Gastrocnemius Medialis (GM) and Vastus Lateralis (VL), relatively higher SI values (more asymmetry) were observed at low speeds (2.9–3.2 km/h). As speed increased (5.0 km/h and above), these indices decreased significantly and the activation distribution between the muscles became

synchronized. This finding supports studies indicating that the increase in energy demand as walking accelerates and the activation of motor control mechanisms by enabling the muscles to work “more organized” are positively reflected in muscle symmetry (Sousa & Tavares, 2012; Moreira et al., 2021). The increased susceptibility of the TA and VL muscles to asymmetry at lower walking speeds indicates that, as speed increases, muscle activation tends to be more symmetrically distributed between the limbs.

As a result, the relationship between muscle activation and walking speed includes muscle-specific differences. Slow-twitch muscles, such as SOL, which contribute more to postural balance, are relatively less affected by speed and maintain a high level of symmetry. In muscles that play an important role in dynamic stability and propulsion, such as TA, GM, and VL, a significant increase in symmetry is observed as speed increases. Double-jointed muscles, such as BF, may exhibit a more unstable pattern from speed changes due to individual differences. This pattern largely aligns with the findings in the literature on the relationship between functional asymmetry, walking speed (Rice & Seeley, 2010; Nasirzade et al., 2017; Bergamini et al., 2024) and shows that the speed factor is as critical as the functions of the muscles in gait analysis.

5.2.5 Frame-Based symmetry analysis. There are many studies in the literature on how walking speed affects symmetry. Bergamini et al. (2024) showed that gait is more asymmetric at low speeds and symmetry improves as speed increases. Similarly, another study by Nasirzade et al. (2017) stated that symmetry improves as speed increases. These findings are consistent with post-hoc comparisons made especially in the Gastrocnemius Medialis, Soleus and Vastus Lateralis muscles. It was observed that the symmetry index was high at low speeds such as 2.9 km/h and decreased as speed increased (5.0 km/h and above).

In the GM muscle in particular, individuals walking at 2.9 km/h exhibited higher symmetry index values, which decreased at 5.0 km/h and beyond. These results are parallel to the findings that low speeds lead to more asymmetry, as stated in studies such as Bergamini et al. (2024) and Nasirzade et al. (2017).

However, no statistically significant difference was observed in the TA ($p = 0.1110$) and BF ($p = 0.8331$) muscles. In the TA muscle, although the symmetry index values tended to decrease with speed, these differences did not reach statistical significance. This is consistent with the findings of Hof et al. (2002). The study indicates that TA showed a speed-independent activation pattern, with activation following phase-dependent patterns, peaking in the early phase of slow walking and in the late phase of fast walking.

In the BF muscle, it was observed that the symmetry index followed a fluctuating pattern in the BF muscle and the standard deviation was quite high especially at 4.0 km/h speed. This situation suggests that the inter-individual differences affect the muscle activation patterns especially at fast walking speeds and prevent the creation of significant differences within the group. The reason why these differences are especially evident at a speed of 4.0 km/h may be related to the fact that this speed is the closest value to the natural walking speed.

The results are consistent with some general trends reported in the literature and confirm the effects of walking speed on gait symmetry. However, individual differences and variability between muscles indicate that there are many factors affecting symmetry. This study allows us to understand in more detail how speed affects muscle activation and symmetry, while also revealing symmetry differences between muscles. It also emphasizes the importance of EMG in gait symmetry analysis. The effect of speed allows us to make a more comprehensive assessment by combining both biomechanical and neuromuscular control factors.

5.3 Correlation Between Speed and Symmetry Index

In this study, the relationship between walking speed and bilateral muscle activity symmetry was evaluated using time domain-based EMG features (MAV, AR, RMS) and frame-based analysis methods. The findings showed significant differences in correlation levels depending on the analysis method and muscle group used. This situation is also supported in literature. It has been suggested that time-domain features extracted from EMG signals may show varying sensitivity depending on muscle structure and the phase

of gait (Phinyomark et al., 2012; Sun et al., 2022). In addition, it has been shown in previous studies that the activation levels of the lower extremity muscles change with the increase in walking speed and this change may have an effect on symmetry (Sousa & Tavares, 2012; Hof et al., 2002; Moreira et al., 2021).

The frame-based analysis method was notable for the moderate to strong negative correlations observed in the VL ($r = -0.680$, $p < 0.001$), GM ($r = -0.507$, $p < 0.001$), and SOL ($r = -0.459$, $p < 0.001$) muscles, distinguishing it from other analytical techniques. These findings show that with the increase in walking speed, activation symmetry in these muscle groups improves, meaning that differences in activation between the two legs decrease. Similarly, the literature reports that an increase in walking speed enhances the activation levels of lower limb muscles such as GM, SOL, and VL (Franz et al., 2012; Hof et al., 2002). In this context, the frame-based analysis approach, thanks to its ability to directly and continuously monitor time-dependent signal variations, contributes to the decrease in the symmetry index due to the speed-based increase in muscle activation, and reveals the right-left differences in the legs more sensitively compared to other methods.

MAV-based analysis results stood out with moderate negative and significant correlations in the TA ($r = -0.369$, $p < 0.001$) and VL ($r = -0.478$, $p < 0.001$) muscles. These findings indicate that the muscles in question tend to exhibit more symmetrical activation as walking speed increases. Similarly, in the literature, it has been stated that the activation of the VL muscle (Moreira et al., 2021) increases with speed and that this muscle is sensitive to dynamic loads. For the TA, Hof et al. (2002) reported that this muscle exhibits a speed-independent activation pattern at some walking speeds but increases in certain phases. Therefore, the MAV feature stands out as an effective indicator in the evaluation of gait symmetry, especially for muscles that show superficial and rhythmic activity. In contrast, the weak correlations obtained in muscles such as the GM and SOL may be due to both the biomechanical roles of these muscles and the inability of MAV to reflect activation patterns in these muscles with sufficient sensitivity.

In AR-based analysis, generally low-level correlations were obtained, but statistically significant relationships were observed in some muscle groups. While weak but significant negative correlations were detected in Tibialis Anterior, Gastrocnemius

Medialis and Soleus muscles, the related significance level was not reached in Vastus Lateralis muscle. These findings indicate that AR features may have limited sensitivity in determining symmetry changes depending on walking speed. However, the moderate negative and significant correlation observed in Biceps Femoris muscle ($r = -0.461$, $p < 0.001$) suggests that this muscle shows a significant activation adaptation to the increase in speed. It has been stated in the literature that Biceps Femoris is activated at an increased level, especially during fast walking, to provide postural balance and contribute to knee flexion (Franz et al., 2012). Therefore, AR features methods may be more successful in reflecting the activation pattern of this muscle that is sensitive to speed changes compared to other muscles. While this situation underlines the muscle-specific effectiveness of the AR analysis method, it also indicates that analysis methods may not show equal sensitivity for all muscle groups.

RMS-based analysis stood out with moderate negative and significant correlations in the TA ($r = -0.443$, $p < 0.001$) and VL ($r = -0.452$, $p < 0.001$) muscles. These findings indicate a significant increase in the activation symmetry of these muscles as walking speed increases. In the literature, it has been reported that the TA muscle has a constant activation pattern at most walking speeds, but an increase in activation level is observed at the beginning of the stance phase at low speed (0.75 m/s) and at the end of the swing phase at high speed (1.75 m/s) (Hof et al., 2002). While TA activation is phase-dependent (Hof et al., 2002), findings suggest improved interlimb coordination with speed. On the other hand, it has been reported that the activation level of the VL muscle increases linearly with increasing speed and that this muscle is activated more similarly in both legs (Moreira et al., 2021). Weak but statistically significant correlations were observed in the SOL and BF muscles, suggesting that these muscles exhibit limited symmetry adaptation to speed changes. The correlation value obtained for the GM muscle was not significant ($r = -0.088$, $p = 0.274$), indicating that either the activation similarity of this muscle in the right and left legs is not greatly affected by walking speed or the RMS feature is not sensitive enough to reflect the signal variations of this muscle.

One of the main contributions of this study is to provide a systematic analysis of how gait symmetry changes as walking speed increases. According to the analysis of symmetry index values, it was observed that in some muscle groups, the activation

differences between the right and left sides decreased with increasing walking speed, indicating more symmetrical patterns were formed. VL and TA muscles showed this tendency in almost every analysis method. It has been stated in the literature that these muscles are activated in a more coordinated way due to their functions of maintaining balance and providing knee/ankle stability against increasing walking speed (Moreira et al., 2021; Hof et al., 2002). In contrast, muscles such as GM and SOL showed weak correlations in some analysis methods, which may be due to either the rapidly changing task profiles of these muscles or the limited sensitivity of the EMG feature used. BF exhibited a moderate symmetry change in AR analysis. This may be attributed to the sensitivity of the muscle in question to increased postural demands due to increased walking speed and to its regular activation pattern compatible with speed (Franz et al., 2012).

The results show that the relationship between walking speed and symmetry index varies depending on both the muscles and the analysis method used, and that this relationship is strong and significant in some muscles, while it is weaker or insignificant in others.

Chapter 6

General Conclusion, Limitations & Future Work

6.1 Conclusion

This study analyzed gait symmetry in detail using electromyography (sEMG) data at different speeds. The findings generally show that as walking speed increases, activation between muscles becomes more balanced and asymmetry between right and left legs decreases. Higher symmetry index (more asymmetry) was observed at low speeds (2.9 – 3.2 km/h), especially in Tibialis Anterior, Vastus Lateralis and Gastrocnemius Medialis muscles, and it was determined that these values decreased statistically significantly at speeds of 5.0 km/h and above, and a more symmetrical muscle activation pattern was achieved. The soleus muscle stood out as the muscle with the lowest symmetry index in general and was less affected by speed changes due to its contribution to postural balance. In contrast, the Biceps Femoris muscle showed high individual variation and exhibited statistically higher individual differences. This situation revealed that speed did not create a fixed symmetry effect on this muscle but the high variation it exhibits, especially at 4km/h, is associated with BF being close to its natural walking speed.

The different EMG analysis methods (MAV, AR, RMS) and frame-based approach used allowed for multi-dimensional evaluation of findings related to symmetry. Time domain features such as MAV and RMS were found to be more sensitive in revealing symmetry differences. In contrast, the AR feature was limited in terms of statistical significance but stood out in terms of reflecting inter-individual variations. Frame-based analysis, on the other hand, contributed to the analysis of individual differences, especially in muscles with high variance, by capturing the temporal flow of the signal sensitively.

This study shows that high symmetry indices are observed especially in Tibialis Anterior, Gastrocnemius Medialis and Vastus Lateralis muscles at low speeds (2.9 km/h, 3.2 km/h), and these indices decrease with increasing speed, especially at speeds of 5.0 km/h and above, and a better symmetry is formed.

In addition, when evaluating walking symmetry, it is seen that muscle-based neuromuscular responses should also be considered together with speed. Each muscle can respond differently to changes in walking speed due to factors such as its function in the body, its interaction with the nervous system and its contraction pattern. Therefore, symmetry is not affected in the same way in all muscles. While some muscles provide balance, others undertake the task of initiating or slowing down movement. These different roles determine the level of symmetry by affecting how the muscles are activated in the right and left legs.

In conclusion, this study offers a multidimensional scientific perspective on human walking by taking into account that walking symmetry varies with speed and functional differences of muscles when evaluated.

6.2 Limitations & Future Work

This study has some limitations. First, the analysis was performed only with data from healthy individuals. Therefore, the applicability of the results to clinical populations (e.g., individuals after stroke or prosthesis users) are limited. In addition, the analysis was performed only in forward walking conditions on flat ground; conditions such as turns, slopes, or unstable ground were not evaluated. EMG signals were obtained from the surface, and information on deep muscle groups could not be provided.

In terms of analytical methods, the three basic time-domain EMG features (MAV, AR, RMS) and the frame-based analysis method used in this study exhibited different sensitivities in assessing gait symmetry. While MAV and RMS features show group differences between muscles more clearly; the AR feature was relatively successful in representing individual variations but was limited in detecting statistical differences at the group level. On the other hand, the frame-based analysis method, although it reflects the temporal flow of the signal in detail, may cause high variance in some muscles, thus amplifying inter-individual differences and limiting the generalizability of the results.

In addition, only three EMG features were used in this study. However, there are more features that can be extracted from EMG signals. In future studies, performing symmetry analysis based on walking speed with a wider set of features can both increase

the sensitivity of the analysis and provide a deeper understanding of muscle behavior. Finally, in future studies, the scope can be expanded by including different age groups, clinical samples, and various walking scenarios (hill, turn, rough ground, etc.).



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