

# Evaluation of Ankle Joint Movements in Frontal Plane for a Normal Coordinated Gait

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## Abstract

As per the records, around 15% of the global population is experiencing some form of disabilities in lower extremity resulting in loss of accessibility to their basic routine movements. The ankle joint complex plays an important role as a weight bearing articulation in the lower extremity and is a key contributor to the power behind human locomotion. While sagittal plane ankle movements are crucial for gait, several studies have proven that inversion-eversion, the frontal plane movements oversee the pressure distribution at the ankle joint to ensure a well-coordinated gait. This paper presents an evaluation of prediction of such ankle joint movements using Electromyogram (EMG), Inertial Measurement Unit (IMU) and Force-Sensitive Resistor (FSR) measurements, which can later be adapted for use in anthropometric active ankle orthosis designs to assist dynamic ankle movements during normal gait in real-time.

*Keywords:* Ankle-joint movements, Frontal plane mechanics, EMG, Active ankle orthoses

## 1. Introduction

The World Health Organization (WHO) estimates an increase in the global population of individuals aged 65 and above, rising from 524 million in 2010 to 1.5 billion by 2050, reflecting a growth from 8% to 16% of the world's population. Alongside age-related degenerations, a larger proportion of the population is anticipated to experience mobility-related impairments caused by chronic diseases [1],[2]. Walking, as the most fundamental human activity of daily life, serves as a critical indicator of individual health, and gait impairments can significantly compromise independence and quality of life. Consequently, understanding and addressing the biomechanical factors contributing to normal and abnormal gait patterns is crucial for improving rehabilitation strategies and outcomes [3].

The ankle joint complex, a critical weight-bearing articulation that supports nearly 100% of the ground force load, plays a key role in locomotion by contributing approximately 45% of the total power required for walking and running [4],[5]. Its primary movements are plantarflexion-dorsiflexion, occurring in the sagittal plane; inversion-eversion, occurring in the frontal plane and abduction-adduction, occurring in the transverse plane. While the ankle is often simplified as a hinge joint facilitating sagittal plane movements for gait analysis, its function is far more intricate involving simultaneous, complex actions across all three planes such as supination and pronation during locomotion [6]. Notably, movements in frontal plane, inversion and eversion play a crucial role in maintaining balance and stability through uniform distribution of ground reaction forces during gait. These movements adjust the foot contact area with the ground, allowing for efficient pressure absorption and

propulsion while minimizing the strain at lower extremities [7],[8].

Given the complexity of ankle biomechanics, evaluating frontal plane movements during normal coordinated gait is particularly important for understanding how these motions contribute to stability and efficiency. Research has shown that frontal plane mechanics play a critical role in dynamic postural control and load redistribution, which are essential for normal gait [9],[10]. The intricate coordination of frontal plane movements with other joint motions ensures proper alignment and minimizes compensatory forces that could lead to injuries or further gait dysfunction. By evaluating the frontal plane ankle joint movements in healthy individuals, researchers can establish baseline parameters for normal gait, which could then be used to develop targeted rehabilitation strategies, particularly through the use of active ankle joint orthosis devices. These devices provide support and assistance on such compromised movement and further it can be customized to individual needs. Therefore, a detailed evaluation of these movements is crucial for optimizing rehabilitation efforts and enhancing the effectiveness of orthotic interventions, especially in the context of a rapidly aging population.

## 2. Considerations for Evaluation

### 2.1. Anatomy of the ankle joint complex

The ankle joint complex is comprised of the talocrural, subtalar, and transverse-tarsal joints, each contributing to the intricate biomechanics of foot movement. The talocrural joint, functioning primarily as a hinge, facilitates plantarflexion-dorsiflexion movements of the foot [11]. However, its oblique axis of rotation suggests a more complex motion than that of a simple hinge joint.

The axis of rotation of the talocrural joint for the respective sagittal plane movements occurs around the line shown in Fig.1(a). The subtalar joint, with its geometry, is primarily responsible for inversion-eversion of the foot. The axis of rotation of the subtalar joint is also oblique, as illustrated in Fig.1(b). This oblique axis allows the subtalar joint to produce multiple motions during plantarflexion-dorsiflexion, resulting in pronation and supination [12]. The transverse-tarsal joint is considered as part of the functionally coupled unit with the subtalar joint due to the nature of shared axis of motion, further contributing to inversion-eversion of the foot [13].

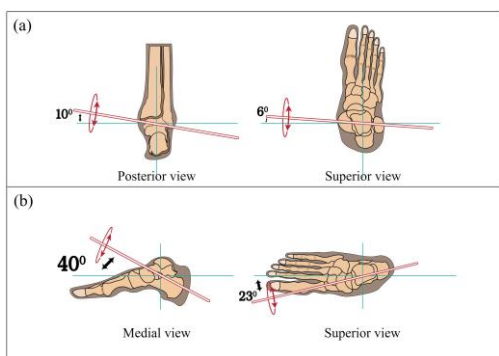


Fig.1. Oblique axes of rotation in ankle joint complex; a) rotational axis of talocrural joint, b) rotational axis of subtalar joint

The motion of the foot and ankle is largely driven by twelve extrinsic muscles, organized into four compartments. The anterior compartment includes four muscles responsible for dorsiflexion and inversion-eversion of the foot, while the lateral compartment contains two muscles that produce plantarflexion and eversion. The posterior compartment consists of three muscles contributing only to plantarflexion, and the deep posterior compartment contains three muscles that facilitate both plantarflexion and inversion of the foot. Understanding the coordinated actions of the ankle joint complex and the related muscles is crucial for the data acquisition processes and evaluations of the dynamic ankle movements [13],[14].

## 2.2. Gait cycle

During walking, each leg follows a repetitive sequence of steps known as the gait cycle, which begins with the heel strike (HS) of one leg and ends with the subsequent HS of the same leg, marking the start of the next cycle. A gait cycle is broadly divided into two phases: the stance phase and the swing phase. The stance phase, comprising approximately 60% of the cycle, considers when the foot is in contact with the ground, beginning at HS and ending at toe-off (TO). Later, the swing phase starts when the foot is off the ground and in motion (see Fig.2(a)) [15].

The HS begins with the ankle in a slightly plantarflexed position, occurring within the sagittal plane, and

transitions to a flat-foot (FF) state. Following this, the ankle moves from plantarflexion to dorsiflexion, facilitating the forward progression of the body during the stance phase. As the heel lifts off the ground, the ankle transitions back into plantarflexion, continuing to its maximum point at TO, where the power generation is achieved to propel the body into the next phase of the gait cycle. During the swing phase, the ankle dorsiflexes to ensure better ground clearance and then repositions to a slightly plantarflexed state, preparing for the next HS (see Fig.2(b)). While these sagittal plane movements dominate the gait cycle, simultaneous movements occur in the frontal plane.

Inversion of the foot is observed up to the HS, enhancing initial ground contact and transitioning to eversion during mid-stance (MST), which facilitates a stable push-off into the swing phase (see Fig.2(c)). Studies have documented an inversion-eversion, within a range of approximately 15 degrees, highlighting the importance of frontal plane dynamics in achieving a coordinated gait [16].

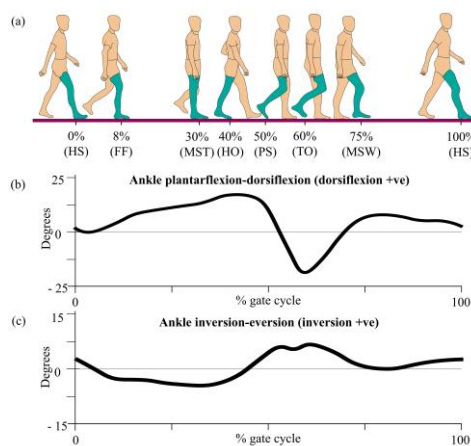


Fig.2. An overview of the gait cycle; a) different states of gait cycle (HO – heel off, PS – pre swing, MSW – Mid swing)[17], b) movements within the sagittal plane across the gait cycle, c) movements within the frontal plane across the gait cycle[11].

## 3. Methodology

### 3.1. Subjects

This study reports experiments conducted on four healthy male subjects (average age: 23 years) who provided informed consent to participate and self-reported no history of biomechanical or neuromuscular disorders.

### 3.2. Experimental setup

The experimental setup included two sensor systems for data acquisition: four wireless surface EMG sensors (Delsys Trigno Avanti), integrated with IMUs, and a four-channel force-sensitive resistor (FSR) sensor

(Delsys Trigno 4-Ch FSR Adapter), enabling precise collection of muscle activity, motion, and foot pressure data during the trials. The sEMG sensors were strategically placed on the muscle bellies of the tibialis anterior, fibularis longus, soleus and gastrocnemius muscles of the right-foot (see Fig.3), as these muscles are known to significantly contribute to ankle joint functions according to previous research [18]. Data from the sEMG sensors were recorded using EMGworks software, developed by Delsys Inc. at a sampling rate of 1926 samples/sec (sa/s) with a bandwidth of 20 – 450 Hz, while acceleration data from the integrated IMUs were captured at a sampling rate of 148 sa/s with a bandwidth of 24 – 470 Hz. The FSR adapter, attached to a sandal, was used to measure the pressure distribution of foot contact with the ground. The FSR membranes were affixed to the inner sole of the sandal, modified to each subject's individual foot configuration to ensure accurate data acquisition. The Fig.4 illustrates the layout of FSR membranes used for different subjects. Data from the FSR sensors were recorded at sampling rates of: 1926 sa/s for channel 1 and 148 sa/s for channels 2 – 4, with a bandwidth of 50 Hz.



Fig.3. Sensor arrangement for data acquisition; a) wireless sEMG sensor assembly, b) wireless FSR sensor attachment

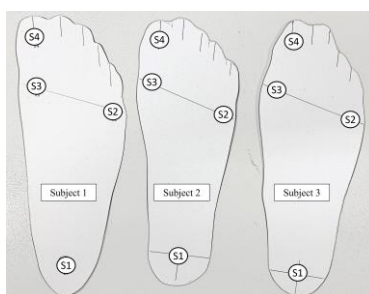


Fig.4. Placement layout of FSR membranes for different subjects based on their unique foot configurations (S1-membrane connected to channel 1, S2 – connected to channel 2 and so on)

### 3.3. Experimental procedure

The subjects were instructed to walk at their normal gait pattern over a fixed distance of 12 meters to collect the data. This test was repeated for five sessions per subject, while maintaining consistent intervals between each session to ensure reliable data acquisition.

## 4. Analysis and Results

The collected data were subjected to a series of steps, including pre-processing, filtering, rectification, and normalization, using a Python program. These steps were performed separately based on each sensor's sampling rate and bandwidth to ensure accurate data handling. Following the processing, the datasets were input into an evaluation model for further analysis. Fig.5 illustrates a sample FSR output acquired from Subject 1. Fig.6 subsequently shows the average EMG waveform along with the calculated EMG envelope, derived to assess the average activation of the EMG signals. These figures provide a detailed representation of the average EMG calculations and the EMG envelopes, facilitating a deeper understanding of muscle activation patterns for further evaluation.

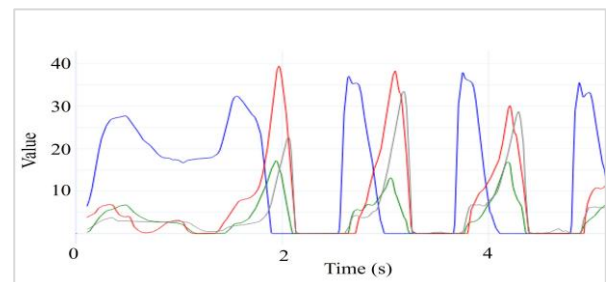


Fig.5. A segment of the FSR sensor output acquired from subject 1 (Blue - pressure sensor 1, Green - sensor 2, Red - sensor 3, Gray - sensor 4)

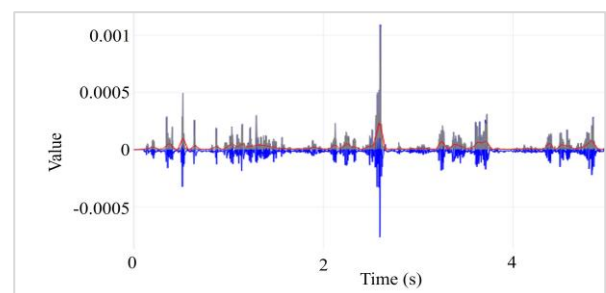


Fig.6. A segment of the EMG envelope corresponds to the original data represented (Blue – original waveform, Gray – avg. rectified waveform, Red – EMG envelope).

## 5. Discussion

This paper emphasizes the significance of evaluating frontal plane ankle joint movements by critically reviewing the key anatomical and gait related factors. The study further discusses the processes and

methodologies that are crucial for assessing dynamic movements within the ankle joint complex, considering its detailed structure. The data obtained in this study demonstrate that a well-defined evaluation model can provide reliable estimations for inversion – eversion movements during normal gait. This approach has the potential to be helpful in optimizing the control of active ankle orthoses, facilitating gait rehabilitation, and offering continuous real-time assistance for individuals with gait impairment, which will be the focus of future studies.

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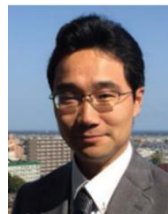
## Authors Introduction

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He received his Bachelor's degree in Engineering from the Faculty of Engineering, University of Moratuwa, Sri Lanka, in 2018. In 2022, he completed his Master's degree at the University of Miyazaki, Japan. He is currently pursuing his Doctoral studies at the University of Miyazaki, Japan.

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