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Quantitative Analysis of Isometric Ankle Torque and Muscle Activity during Dorsiflexion and Plantarflexion

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Abstract

Foot and ankle movements are essential in various activities like walking, running, and balance, where the mechanics of these movements are affected by the muscles around the ankle joint [1,2]. In this study, the correlations between isometric ankle torque and muscle activity of the tibialis anterior (TA) and gastrocnemius (GAS) in the course of dorsiflexion and plantarflexion was investigated. Eight healthy participants were enrolled for the study, where the ankle torque and surface Electromyography (sEMG) of the main flexors were measured and analyzed. The results showed that ankle torque is higher in plantarflexion than dorsiflexion. In addition, the TA has greater muscle activity during dorsiflexion, while the GAS presents higher activity through plantarflexion. Additional investigation using power spectrum density analysis of the recorded sEMG was conducted and it shows the influence of fast twitching muscles on the isometric ankle torque. The outcomes of this work have the potential for developing and assessing new rehabilitation strategies.

***Keywords**: Dorsiflexion, isometric ankle torque, Planter-flexion, sEMG.*

1. Introduction

The ankle joint represents a synovial joint facilitating a wide range of motion, encompassing dorsiflexion (upward movement of the foot) and plantarflexion (downward movement of the foot). Three types of muscle contractions are identified concerning motion activity, namely concentric, eccentric, and isometric, each generating force or torque. Isometric ankle torque denotes muscle-generated torque while maintaining the ankle joint in a fixed position. This torque plays a crucial role in the evaluation of ankle health, provides an indicator of the severity of ankle injuries, and assists in the monitoring of recovery progress [3,4,5,6].

The dorsiflexor muscles are a major contributor in the swing phase and regulate plantarflexion during a heel strike, while the plantarflexor muscles are essential for daily activities such as stair climbing and walking. The normal range of motion (ROM) of the ankle during dorsiflexion is 10-20 degrees and 25-30 degrees during plantarflexion, contributing to inversion and eversion [7, 8, 9]

Ankle injuries represent the most frequent type of injury encountered during exercise and sports activities. It is hypothesized that the plantarflexors and dorsiflexors may exert a protective effect against such injuries [10]. The ankle plantarflexors may raise the risk of an anterior cruciate ligament and knee injury, while, dorsiflexion cannot bear the same capacity of a shock compared with their counterparts [10, 11]. Fong et al. conducted a systematic review in 24 out of 70 sports studies, it showed that the most common site of injuries is the ankle joint [12]. In addition to sprains and fractures, there are more conditions that may lead to ankle dysfunctions or impairments such as osteoarthritis, peripheral nervous compression, peripheral nerve trauma, peripheral neuropathy, cerebrovascular accidents, and spinal cord injuries [13].

Studying ankle torque is important due to the fact that the ankle joint preserves postural stability, can manage the gait, and maintain the functioning of the lower limb. In addition, ankle joint is crucial in various physical activities like walking, running, jumping, and equilibrium control. Ankle torque analysis offers awareness into the neuromuscular coordination and muscular strength of the anatomic structures surrounding the ankle joint, which contains the calf muscles, such as the gastrocnemius and soleus, as well as the muscles located on the anterior of the lower leg, like the tibialis anterior.

Some studies have been conducted to find the relationship between the ankle joint torque and the EMG. Ugbolue et al. [10] conducted an investigation to distinguish the differences in joint angles, including (ROM), forces, and moments between the left and right limbs at the ankle, knee, and hip joints during dynamic dorsiflexion and plantarflexion movements in both males and females. The results revealed the effects of gender, sidedness, phases, and foot position on joint angles. In addition, this study offers data for clinicians and biomechanics working on lower limb exercise interventions and modelling efficacy standpoints [10].

Different machine learning approaches can be used to assess the ankle joint torque that are useful in controlling the robotic-powered exoskeletons to assist patients with movement disorders. A combination of electromyography (EMG)-driven neuromusculoskeletal (NMS) model and an artificial neural network (ANN) model has been used to examine the ankle joint toque in seven movement tasks, encompassing activities such as fast walking, slow walking, and self-selected speed walking, as well as isokinetic dorsi/plantar flexion at different angles [11]. In addition to the surface EMG, developed nonlinear mathematical models had been used by [14] to estimate the ankle joint torque by utilizing Swarm techniques to identify model parameters for dorsiflexion and plantarflexion pattern of the ankle. Such a model can also help to control robotic rehabilitation for improving body movements.

Lateral ankle sprains (LAS) are a prevalent form of injury experienced by both athletes and non-athletes alike. This type of injury is responsible for a significant number of emergency room visits in different countries each year, with over one million recorded annually. Therefore, understanding such an injury by studying the foot posture such as ankle inversion, internal rotation, plantarflexion, and strength is fundamental for preventing injury and finding a reliable plan for rehabilitation protocols [15,16,17].

Joint flexibility can be assessed by a universal parameter which is the range of motion (ROM). The relationship between joint flexibility and muscle size has been studied in several joints [18]. The utilization of non-invasive techniques, such as electromyography, poses a significant challenge due to the interference of signals originating from adjacent muscles or the stimulation artifacts induced by functional electrical stimulation (FES). Therefore, Zhang, Q. et al. [19] suggested that a combination of an ultrasound (US) sonography with the EMG signal could enhance the visualization of the muscles and lead to improved prediction accuracy of the volitional ability [18]. However, another study examined joint flexibility and related muscle action using ultrasound and magnetic resonance (MRI) for better assessment [19].

The current work is driven by developing an approach to assess ankle health based on isometric contraction of two flexors, the tibialis anterior and gastrocnemius. This has been achieved using a quantitative analysis of ankle torque and sEMG of the TA and GAS. The results of the study will help us learn more about how we can enhance the performance and function of our ankles.

During the gait cycle, the ankle joint experiences dynamic loads. Some studies have characterized it as a hinge joint that allows flexion and extension movements of the foot primarily in the sagittal plane [20,21], while the subtalar joint is responsible for inversion and eversion movements.

In the current work, we estimated the isometric torque at the ankle joint during dorsiflexion and plantarflexion movements. A cantilever model of the foot is adopted where the lever arm is a perpendicular distance from the center of pressure on the force plate to the ankle joint center. Ankle torque is then calculated by multiplying the lever arm by the force created by the center of pressure of the foot. The anatomical landmarks of the head of the fifth metatarsal bone and the lower extremity of the external malleolus are used as reference points to determine the lever arm. This model is widely used in biomechanics research due to its practicality and simplicity. However, it is important to note that for precise estimations of ankle torque, sophisticated models should be used.

Such models should consider individual anatomical variations, muscle-tendon dynamics, and the intricate interactions within the foot segments. The adoption of such a complex model is outside the scope of the current study since our focus is on isometric contractions only.

2. Methodology

Surface electromyography (sEMG) is a non-invasive technique used for measuring the electrical activity of the muscles. In this technique, surface electrodes are placed between the motor unit and the muscle insertion to detect the electrical signals generated by muscle contractions. These signals provide information regarding muscle activation and can be analyzed to observe muscle enrollment patterns [22,19]. We have employed sEMG to investigate their correlation with generated torque in the ankle during both dorsi and plantarflexion movements. Our focus was on two major flexors, the TA muscle as the primary flexor responsible for ankle dorsiflexion, and the GAS muscle as the primary flexor for ankle plantarflexion. By examining the sEMG patterns of these muscles, we have clear understanding of their activation levels and contribution to the overall ankle torque production. It is important to note that the opposite side should be tested using the same procedure to ensure consistency and determine any potential bilateral differences. The ankle dorsiflexion, which is the weaker function compared with plantarflexion, was tested first. Such testing procedure enabled the participants to become familiar with performing maximum voluntary contractions before proceeding to plantarflexion testing. To measure ankle dorsiflexion torque, we firmly strapped the distal region of the foot's metatarsal to concentrate the exerted force at this specific area and stabilize the foot. Participants were then instructed to pull up against the strap to flex the ankle. Moreover, for ankle plantarflexion torque measurement, we placed the strap on the distal region of the thigh and passed it over the external malleolus. Participants were asked to pull against the strap by extending their ankle while simultaneously pushing with the sole of their foot, attempting to lift the heel.

Table 1,
Biometric information of the eight participants.

participants	Age	Height/cm	Weight/Kg	Lever-arm/cm	Gender
Participant1	25	181	69.5	0.14	Male
Participant2	26	174	101	0.149	Male
Participant3	23	188	74	0.125	Male
Participant4	23	169	69	0.13	Male
Participant5	22	178	88	0.15	Male
Participant6	23	159	59	0.1	Female
Participant7	23	162	60.5	0.12	Female
Participant8	23	170	72.6	0.12	Male

Three trials were conducted, each consisting of 2-4 seconds maximal contractions, with a 30 second rest period between each trial. The maximal torque was calculated as the product of the measured force and the lever arm. The testing protocol enabled the accurate assessment of ankle torque in both dorsi and plantarflexion movements. By obtaining multiple trials and computing maximal torque values, we ensured robust and reliable data for further analysis and interpretation. The lever arms were measured for each participant, and the force was recorded by the force plate to calculate the torque around the ankle joint. On the other hand, the sEMG activity data were transferred to MATLAB for preprocessing, and to compute the amplitudes of the sEMG

3. Participant Enrollments and Experimental Setup

This experiment was conducted in the university of Baghdad, Al Khwarizmi college of engineering, Biomechanics lab. In this study, a total of eight healthy participants without any musculoskeletal or neurological disorders that could potentially impact lower extremity function were enrolled. All participants have provided an informed consent and their personal information was treated confidentiality.

Table 1 presents the characteristics of the participants in this research. To measure the reaction force of the foot, a Vernia force plate was used and data acquisition was achieved using a LabQuest device. The participants were placed on an adjustable height stool to ensure a right angle at the hip, knee, and ankle joints. The leg was kept vertically and the foot set flat on the force plate, as illustrated in Figure (1). This setup reduces the impact of segment weight, which may affect the reaction force.

Before recording sEMG, we considered several preparation measures to ensure the experiment's accuracy. First, we request participants not to bring their phones into the experimental area to prevent wireless interference since the sEMG sensor is based on wireless technology.

Second, we have prepared the equipment and ensuring the integrity of the cables for the force plate and the Go-direct Vernier EKG sensor, which we used to measure sEMG activity. Third, we carefully considered the participant setup, which is an essential aspect of our procedure. This includes the target muscles that we intend to record sEMG activity, the TA and GAS muscles. We instruct each participant to cleanse the skin area of the target muscles where the surface electrodes will be placed, ensuring it is free from hair or dead skin. We then apply a small amount of specialized conductive gel to reduce resistance between the electrodes and the skin.

Adhesive electrode pads were used to ensure secure attachment to the skin and consistent contact with the underlying muscles. Data acquisition and analysis were carried out using a PC equipped with Vernier Graphical Analysis and MATLAB software.

Figure (1) illustrates the experimental setup adopted in this study. To measure dorsiflexion, a non-elastic strap was positioned and secured on top of the foot at the level of the first metatarsal. We instructed the participants to perform the dorsiflexion movement which is raising the foot upward against the force plate while the sEMG and torque are recorded simultaneously.

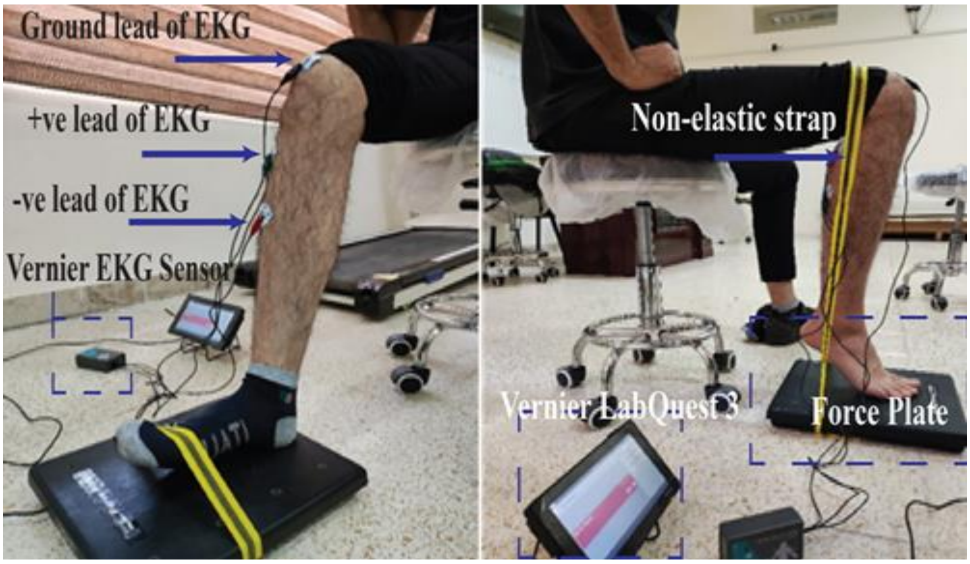

Fig. 1. The experimental setup.The positive and negative electrodes were placed on the upper part of the dominant leg's Tibialis Anterior muscle for each participant. Additionally, the positive and negative electrodes were positioned on the lateral side of each subject's gastrocnemius muscle A-The dorsiflexion setup. B-The plantarflexion setup.

For plantarflexion measurement, the strap was placed distally on the thigh and passed directly over the external malleolus to prevent any movement during the procedure, thus ensuring stability during the testing protocol. After this preparation, we requested the participants execute the plantarflexion movement, which moves the foot downward.

4. Results and Discussion

The outcomes displayed in Figure 2 shows the torque values for dorsiflexion and plantarflexion across the participants. Notably, the torque values observed during plantarflexion are consistently higher than those during dorsiflexion for all participants. This observation aligns with previous findings [23]. Participants 5, 6, and 7 exhibit less variability in their torque values compared to the other cases.

This pattern could be attributed to the fact that these participants are females with a lower body mass index and relatively lower muscle density. sEMG signals were acquired from the participants, specifically targeting the GAS and TA muscles during plantar and dorsiflexions, respectively. These muscles are known to be the primary contributors to their respective flexion movements. Figure (3) illustrates the raw sEMG signals, which are subsequently rectified and filtered to improve analysis and interpretation. signal is proportional to the level of muscle activation.

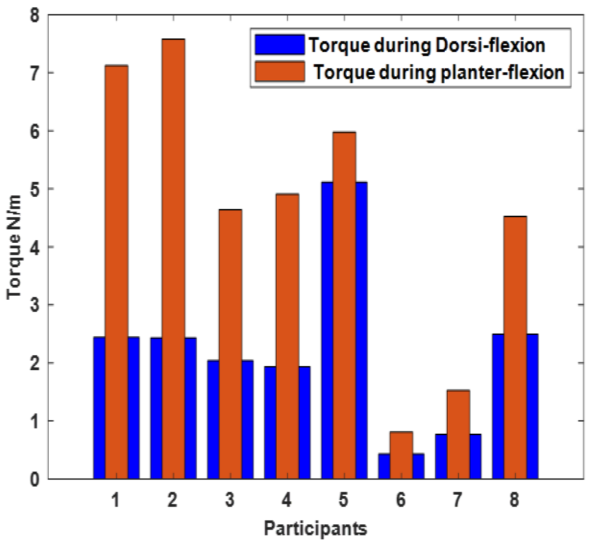

Fig. 2. Torques of the dorsiflexion and planter flexion for each participant.

This process enhances the visibility and interpretability of the signal during analysis. Filtering the sEMG signals allows for the selection of a specific frequency range of interest while eliminating frequencies outside that range. In the case of sEMG analysis, a common range of interest is typically between 20 Hz and 500 Hz [24][27]. Generally, the TA exhibits higher muscle activity compared to the GAS, except for Participant 1. Although this may initially seem counterintuitive, it can be explained by the significant role of the TA as the primary ankle dorsiflexor during dorsiflexion. This muscle contracts to raise the foot upwards, acting in opposition to the GAS muscle, where higher muscle activity in the TA is expected during ankle dorsiflexion compared to the GAS

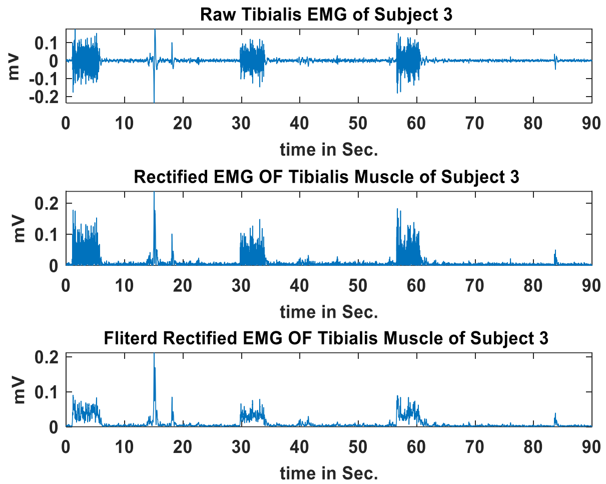

Fig. 3. Rectification and filtration of sEMG signals from tibialis muscle: Participant 3

Filtering the sEMG signals allows for the selection of a specific frequency range of interest while eliminating frequencies outside that range. In the case of sEMG analysis, a common range of interest is typically between 20 Hz and 500 Hz [24][27]. Generally, the TA exhibits higher muscle activity compared to the GAS, except for Participant 1. Although this may initially seem counterintuitive, it can be explained by the significant role of the TA as the primary ankle dorsiflexor during dorsiflexion. This muscle contracts to raise the foot upwards, acting in opposition to the GAS muscle, where higher muscle activity in the TA is expected during ankle dorsiflexion compared to the GAS. In plantarflexion, the GAS acts as the primary ankle plantarflexor, while the TA relaxes. This will raise the muscle activity of the GAS during ankle plantarflexion compared with the tibialis anterior. Referring to Figure 4, the obtained mean values of the rectified sEMG are small, except for Participant 5, which may be attributed to individual and anatomical differences between the two muscles. This high activity in the TA compared to the GAS can be attributed to the TA's larger cross-sectional area, enabling it to generate higher force in comparison with the GAS [24].

We acknowledge the individual variability in muscle activation levels while performing the protocol, where each participant may exhibit unique patterns of muscle activation and these differences should be taken into account during analysis and interpretation. The power spectral density (PSD) of sEMG signals provides valuable insights into the distribution of power across different frequencies in the electrical activity of muscles. It serves as a useful tool for identifying various types of muscle contractions [25].

Figure (5) shows the relation between the PSD of two typical participants, 3 and 4, in which other results from participants showed the same pattern. This pattern showed that PSD is higher in TA than that obtained from GAS in which the largest power is noticed to be located in the frequency range > 75 Hz. The TA consists predominantly of fast-twitch muscle fibers, while the GAS contains predominantly slow-twitch muscle fibers.

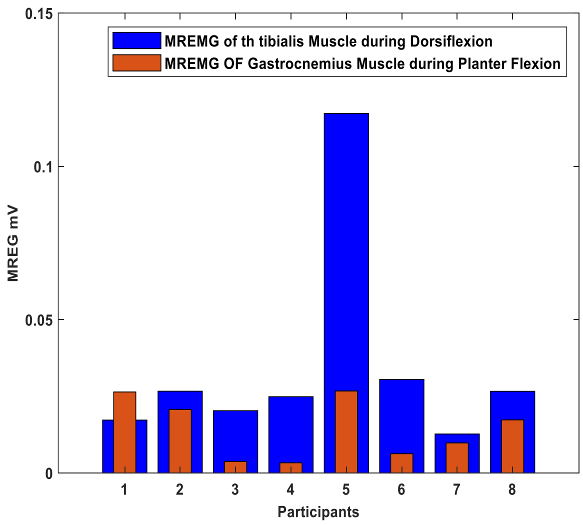

Fig. 4. Mean REMG of TA and GAS muscles (each participant)

This characteristic enables the TA to generate higher force output but also makes it more susceptible to fatigue [26].

Referring to [23], our results are generally in line with the findings obtained from it regarding dorsi and plantarflexions. However, our analysis of the sEMG activity of the primary flexors can be considered as a valuable addition to investigating the correlation between ankle torque and muscle activities. Nonetheless, further investigations should be conducted to explore the impact of other flexor muscles on plantarflexion and dorsiflexion in order to gain a comprehensive understanding of muscle activation and isometric ankle torque.

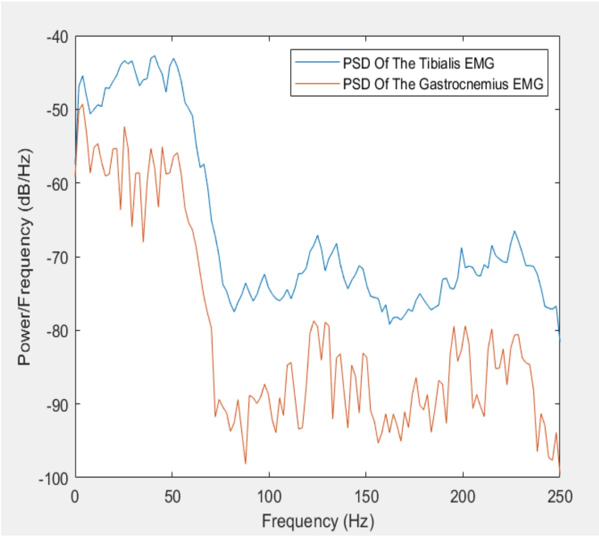

Fig. 5. PSD of the Tibialis and Gastrocnemius EMG

5. Conclusion

The present study intended to explore the correlation between isometric ankle torque and the muscular activity of the tibialis anterior and gastrocnemius during plantarflexion and dorsiflexion movements. It shows that the torque values during plantarflexion are higher than those during dorsiflexion for all participants, except for three participants who showed less variability in their torque values. This variability could be referred to their lower body mass index and lower muscle density. The rectified sEMG show that the muscle activity of TA is higher than GAS because it has a larger cross-sectional area which makes TA produce higher force. The power spectral density (PSD) is greater in TA compared with GAS, which can be attributed to TA's possession of a greater proportion of fast-twitch fibers. However, this particular feature enables TA to generate a higher force output but makes it more prone to fatigue. Nevertheless, additional research must be undertaken to examine the influence of other flexor muscles on both plantarflexion and dorsiflexion, with the aim of acquiring a comprehensive understanding of muscle activation and isometric ankle torque. For future work and to enhance our findings, we plan to increase the number of participants and invite more female participants to strengthen the outcomes.

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التحليل الكمي لعزم دوران الكاحل المتجانس والنشاط العضلي في كل من الانقباض الظهري و الباطني

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الخلاصة

تعتبر حركات القدم والكاحل، مثل الثني الظهري (رفع القدم لأعلى) والثني الأخمصي (توجيه القدم لأسفل)، أساسية لمجموعة من الأنشطة اليومية مثل المشي والجري والحفاظ على التوازن. حيث تعتمد الميكانيكا الحيوية المناسبة في هذه الحركات على تنسيق عالي بين لكل عضلة حول مفصل الكاحل.
في هذا البحث تم التحقق من العلاقة بين عزم دوران الكاحل متساوي القياس والنشاط العضلي لعظلة الظنبوب الأمامية وعضلة الساق البطنية أثناء الثني الظهري والثني الأخمصي. اشتملت الدراسة على ثمانية أشخاص أصحاء، وتم استخدام قياس النشاط الكهربي للعضلة السطحي (sEMG) لتسجيل نشاط العضلات. أظهرت النتائج أن عزم الكاحل كان أعلى أثناء الانثناء الأخمصي مقارنة بالانثناء الظهري. علاوة على ذلك ، أظهر عضلة الظنبوب الأمامية نشاطًا عضليًا أكبر أثناء الانثناء الظهري ، بينما أظهر عضلة الساق البطنية نشاطًا أعلى أثناء الثني الأخمصي. تلقي هذه النتائج الضوء على الميكانيكا الحيوية للكاحل ولما لها من آثار محتملة على التدخلات السريرية واستراتيجيات إعادة تأهيل القدم. هذه الدراسة تعطي تبريرا كافية لإجراء مزيد من البحث حول أدوار عضلات الثني الأخرى في حركات الكاحل للحصول على رؤى شاملة حول تنشيط العضلات وعزم دوران الكاحل متساوي القياس.