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Research Article

Gastrocnemius and Soleus Muscle Contributions to Ankle Plantar Flexion Torque as a Function of Ankle and Knee Angle

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Abstract

Understanding the relative and absolute contribution each muscle can make to Plantar Flexion Torque (PFT) as a function of joint angles is fundamental to understanding the role these muscles play in various tasks, to characterizing the strain induced in the Achilles tendon under varying joint configurations and muscle activation levels, and to creating accurate musculoskeletal models and movement simulations. The purpose of this study was to quantify the absolute and relative contributions the gastrocnemius and soleus muscles make to PFT as a function of ankle and knee angles in endurance level athletes. Compared to previous studies, a more pronounced knee flexion angle was considered to ensure having a joint configuration with minimal gastrocnemius PFT contribution. A variety of ankle-knee combinations were tested to estimate the contributions of the gastrocnemius and soleus for a full range of ankle and knee joint motion. The maximum average total PFT for various knee and ankle combinations was 105.6 + 25.9 Nm and occurred for ankle and knee angles of 75˚ and 90˚ respectively. The gastrocnemius contributed to the ankle PFT for all joint angle combinations except the most plantar flexed ankle and flexed knee. Gastrocnemius PFT contributions were 40% or higher in a fully extended knee position compared to a flexed knee position, for all ankle combinations.

Keywords: Mechanics; Gait

Introduction

The gastrocnemius and soleus muscles act synergistically to produce ankle plantar flexion torque, play an important role in many forms of locomotion, and are central to several clinically relevant conditions. Understanding the relative and absolute contribution each muscle can make to Plantar Flexion Torque (PFT) as a function of joint angles is fundamental to understanding the role these muscles play in various tasks, to characterizing the strain induced in the Achilles tendon under varying joint configurations and muscle activation levels, and to creating accurate musculoskeletal models and movement simulations.

The biarticular and uniarticular nature of the gastrocnemius and soleus respectively provide the opportunity to characterize individual muscle contributions to ankle PFT by testing individuals as they systematically produce maximum ankle plantar flexion efforts for various ankle and knee joint angle combinations. The gastrocnemius muscle length and force producing capability are affected by knee angle changes, while the soleus length and force capability are not. Thus, it is possible to quantify gastrocnemius and soleus PFT contributions by testing maximum PFT for specific ankle-knee angle combinations. It is generally accepted that there is little ankle PFT generated by the gastrocnemius at pronounced knee flexion angles due to the decreased length of the gastrocnemius and active insufficiency [1-4], but the exact knee flexion angle beyond which the gastrocnemius contributes little to PFT is not clear. A few investigators have assumed the gastrocnemius PFT contribution to be negligible for knee flexion angles greater than 90˚(included angle) [5,6] while other investigators have shown that the gastrocnemius muscle contributes to PFT up to 60˚ of knee flexion [2].

Few human studies have been performed to estimate the gastrocnemius and soleus contributions to PFT. Cresswell, et al. (1995) reported the gastrocnemius contribution to PFT to be at least 40% of the total torque at a fully extended knee position [2]. Maganaris (2003) reported that for a fully extended knee, the gastrocnemius contribution to PFT increases with ankle dorsiflexion from approximately 34 Nm at 120˚ included ankle angle to 77 Nm at a 70˚ angle [5]. Ardnt, et al. (1998) concluded the soleus contributed 60.3 Nm to PFT at a 90˚/90˚ ankle-knee combination, while the gastrocnemius contributed nothing [7]. By increasing the knee angle to 170˚, the gastrocnemius PFT contribution increased to 53.4 Nm. There is clearly limited information regarding the absolute and relative gastrocnemius and soleus contributions to PFT as a function of ankle-knee angle combinations.

The objectives of the present study were to quantify the absolute and relative contributions the gastrocnemius and soleus muscles make to PFT as a function of ankle and knee angles in collegiate level endurance athletes. Compared to previous studies, a more pronounced knee flexion angle was considered to ensure having a joint configuration with minimal gastrocnemius PFT contribution. A variety of ankle-knee angle combinations were tested to estimate the contributions of the gastrocnemius and soleus for a full range of ankle and knee joint motion.

Methods

Subjects

Ten collegiate level endurance athletes (5 males and 5 females) participated in this study (average age, height, and mass ± one standard deviation were 20 ± 1 years, 172 ± 7 cm, and 62 ± 6 kg, respectively). All subjects were healthy, without any known neuromuscular disorders or current lower extremity injuries. Subjects volunteered and gave informed consent prior to testing. The study was approved by the University of California, Davis Institutional Review Board

Experimental Protocol and Torque Measurements

Subjects performed Isometric Maximum Ankle Plantar Flexion Efforts (IMAPFEs) while positioned on a modified incline bench (Figure 1). The bench was equipped with an ankle torque transduction system that allowed testing of various ankle-knee angle combinations. The ankle angle was defined as the included angle between the shank and the sole of the foot, while the knee angle was defined as the included angle between the shank and thigh (180˚ refers to full extension). The lateral malleolus was aligned with the axis of rotation of the ankle torque transduction system. The ball of the foot was secured to the footplate using Velcro straps. Knee and/or shoulder restraints were utilized to prevent anterior displacement of the body during IMAPFEs.

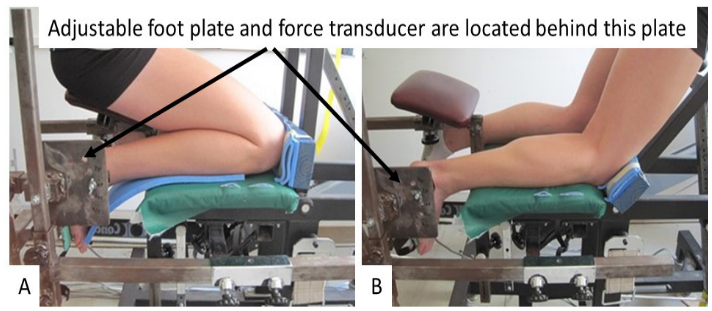


Figure 1: Images of a subject positioned on the modified incline bench for ankle/knee angle combinations of 90˚/30˚ (A) and 90˚/120˚ (B). The incline bench was equipped with an ankle torque transduction system, consisting of a force transducer and an adjustable footplate that allowed testing of various ankle and knee angle combinations.

Subjects attended two testing sessions with at least one day of rest between sessions to reduce the possibility of fatigue. Subjects began each testing session with a brisk six minute warm up walk. Subjects familiarized themselves with each ankle-knee angle position by performing submaximal plantar flexion efforts prior to performing three ramped 5 second IMAPFEs. A total of 12 ankle-knee angle combinations were tested (Table 1) in a randomized order (half on each testing day). Subjects were given 1-2 minutes to rest between efforts for a given ankle-knee configuration and a minimum of 4 minutes to rest before testing at a different ankle-knee configuration.

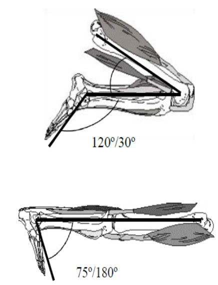
Combinations used for the isometric maximum ankle plantar flexion effort		
Ankle angle (°)	**Knee angle (°)**	
120	30	
120	60	
120	90	
120	120	
105	30	
90	30	
75	30	
75	60	
75	90	
75	120	
75	150	
75	180	

Table 1: List of the ankle-knee angle combinations tested (left). The joint configuration providing the shortest gastrocnemius length and longest gastrocnemius length tested are shown (right, top and bottom. respectively). The soleus length is not affected by knee angle, but its shortest and longest length would also occur in for the two configurations shown (right, top and bottom. respectively) due to the range of ankle angles represented.

The passive and peak total forces applied to the footplate for each ankle-knee angle combination were measured and used to estimate passive, peak total and peak active PFT. The perpendicular distance between the axis of rotation of the ankle torque transduction system and where the foot contacted the footplate was multiplied by the footplate force to calculate the passive and total peak ankle PFT. Passive PFT was estimated from the force recorded prior to the start of an IMAPFE (i.e. with the foot resting on the footplate). Peak total PFT was estimated from the peak force measured during an IMAPFE. Active PFT was calculated as the peak total PFT minus the passive PTF for each trial. The average passive, peak total, and peak active PFT were determined from three repetitions.

Determination of Gastrocnemius and Soleus Contributions

Gastrocnemius and soleus passive, total and active PFT contributions were quantified for the ankle-knee angle combinations tested (Table 1) as well as for fixed ankle angles of 105° and 90° combined with knee angles of 60°, 90°, 120°, 150°, and 180°, which were not tested. Two assumptions were made to calculate gastrocnemius and soleus contributions for ankle-knee angle combinations that were not tested: 1) the gastrocnemius contributes no PFT for a fully plantar flexed ankle angle (120°) combined with a fully flexed knee angle (30°); and 2) the ratio of the gastrocnemius moment arms at the knee and ankle is 1:2 for all ankle-knee angle combinations considered. The validity of the first assumption was demonstrated in pilot experiments in which we found negligible decreases in PFT as the knee was flexed from 45° to 30° with the ankle angle fixed at 120°. The second assumption was based on previous literature reports of moment arms in a fresh and "robust" human cadaver [8], and approximate moment arms extracted from other studies [9,10].

Utilizing the first assumption, gastrocnemius and soleus contributions to PFT were estimated for all knee angles associated with a fixed ankle plantar flexion angle of 120°. If the gastrocnemius contributes no PFT at an ankle-knee angle combination of 120°/30°, then the measured PFT for this joint configuration would be entirely due to the contribution of the soleus. With knee extension, increases in PFT would be due to gastrocnemius contributions since the soleus does not cross the knee joint. Thus, gastrocnemius and soleus PFT contributions can be distinguished for all knee angles tested in combination with a fixed 120° ankle angle.

Utilizing the second assumption and testing specific ankle-knee angle combinations, we were able to minimize the number of tests required and thus muscle fatigue, while being able to characterize gastrocnemius and soleus PFT contributions over a larger range of ankle-knee angle combinations than was tested. As a first approximation, if the trajectory of tendons is characterized as following an arc, then it is possible to estimate muscle-tendon length changes from joint angle changes utilizing the mathematical relationship $S = r \times \Theta$ (where S is equal to the muscle-tendon length change, r is equal to the moment arm, and Θ is equal to the change in joint angle). Likewise, for biarticular muscles with known moment arm length ratios at the two joints, it is possible to identify angle changes for the two joints that produce the same muscle-tendon length changes. Theoretically, for a gastrocnemius with a 1:2 knee to ankle moment arm ratio, a 15° increase in ankle plantar flexion angle produces the same gastrocnemius length change, and force producing capability change, as a 30° decrease in knee flexion angle. Ankle and knee angles used in this study were chosen in 15° and 30° increments, respectively, to produce ankle-knee angle combinations that provided similar gastrocnemius length and force producing capability changes. For example, the change in gastrocnemius PFT capability as the knee angle increased from 30°

to 60° with the ankle held fixed at 120° would be the same change that would occur if the ankle angle changed from 120° to 105° with the knee angle fixed at 30°.

Results

Plantar Flexion Torque

The magnitude of the peak PFT varied considerably between subjects and was achieved at varying knee angles (Table 2). Values ranged from 74.2 Nm to 187.6 Nm and were achieved with a 75° ankle angle and a knee angle that varied between 90° and 180°.

Subject Gender	Peak PFT (Nm)	Ankle/knee angle combination for Peak PFT (°)
F	74.2	75/90
F	82.7	75/90
F	87.9	75/90
F	118.7	75/120
F	129.8	75/150
M	90.0	75/120
M	105.8	75/90
M	119.0	75/120
M	143.0	75/120
M	187.6	75/180
Average	113.9	
Std dev	34.1	

Table 2: Peak PFT for all subjects along with the ankle-knee angle combination associated with the peak value. Peak PFT was achieved by all subjects with their ankle in the most dorsiflexed position, but the knee ankle varied from 90° to 180°.

PFT increased with dorsiflexion. With the knee fully flexed (30° angle), and the ankle fully plantar flexed (120°), passive PFT was zero and subjects generated their least average total PFT, 7.7 Nm (±2.5) or 7.1 % (±2.9) of maximum average total PFT (Table 3). Full dorsiflexion of the ankle (75°) showed an average passive PTF contribution of 2.4 Nm (±2) or ~2.2% of maximum average total PFT. With the knee angle fixed at 30°, both average total and active PFT increased with ankle dorsiflexion to 67.9 Nm (±33.4) and 65.5 Nm (±31.8), respectively, at an ankle angle of 75°.

Passive PFT increased with knee extension from the fully flexed knee position, while the total and active PFT tended to increase and then decrease slightly. Extending the knee from 30 to 90° resulted in a 9.6 Nm increase in average total and active PFT (range 2-14 Nm). By extending the knee further to 180°, subjects on average increased their total and active PFT to 29.3 Nm (±14) or 23.1% (± 2.5) of max average total PFT. With the ankle locked in a dorsiflexed position of 75°, extending the knee from 30 to 90° resulted in an average passive PFT increase of 1 Nm and average total and active PFT increases of 37.7 Nm and 36.7 Nm, respectively. The average maximum total and active PFT of 105.6 Nm (± 25.9) and 102.2 Nm (±24.8) were attained at a 75°/90° ankle-knee angle combination, but the knee angle at which peak total and active PFT was achieved varied between subjects (Table 2). Increasing the knee angle to full extension resulted in the greatest average passive PFT of 6.4 Nm (±3.5) or ~6% of maximum average total PFT; however, average total and active PFT decreased to 97.3 Nm (±37) and 90.9 Nm (± 34.8), respectively.

Ankle Angle (°)	Knee Angle (°)	Avg. Passive PFT (Nm)	Avg. Total Peak PFT (Nm)	Avg. Active Peak PFT (Nm)
120	30	0.0	7.7±2.5	7.7±2.5
120	60	0.0	13.4±5.1	13.4±5.1
120	90	0.0	17.3±5.0	17.3±5.0
120	120	0.0	19.4±6.0	19.4±6.0
105	30	0.0	17.6±5.1	17.6±5.1
90	30	0.3±0.3	33.6±11.4	33.3±11.9
75	30	2.4±2.0	67.9±33.4	65.5±31.8
75	60	2.9±0.8	93.0±25.7	90.1±25.2
75	90	3.4±1.4	105.6±25.9	102.2±24.8
75	120	4.5±2.4	101.3±37.1	96.9±35.2
75	150	5.6±2.7	96.8±37.6	91.2±35.8
75	180	6.4±3.5	97.3±37.0	90.9±34.8

Table 3: Average passive, total peak, and active Plantar Flexion Torque (PFT) (± 1 std dev) as a function of ankle and knee angles.

Gastrocnemius and Soleus Muscle Contributions to Active Plantar Flexion Torque

With the knee fully flexed, the absolute peak active PFT increased with dorsiflexion with the gastrocnemius contributing more to this increase compared to the soleus (Figure 2). The gastrocnemius active PFT was assumed to be zero for the 120°/30° ankle/knee angle combination. For this combination, the gastrocnemius muscle is in its most shortened positioned and 100% of the passive, total, and active ankle PFT is attributed to the soleus (Figure 2) with an average passive PFT of 0 Nm and

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average total and active PFT of 7.7 Nm (± 2.5). For a dorsiflexion angle of 75°, the gastrocnemius had an average active PFT of 11.5 Nm (± 5.1) and contributed 19.3% (± 8.5) to the average total PFT, while the soleus average active PFT was 53.8 Nm (± 28.7) and 80.7% of the total PFT.

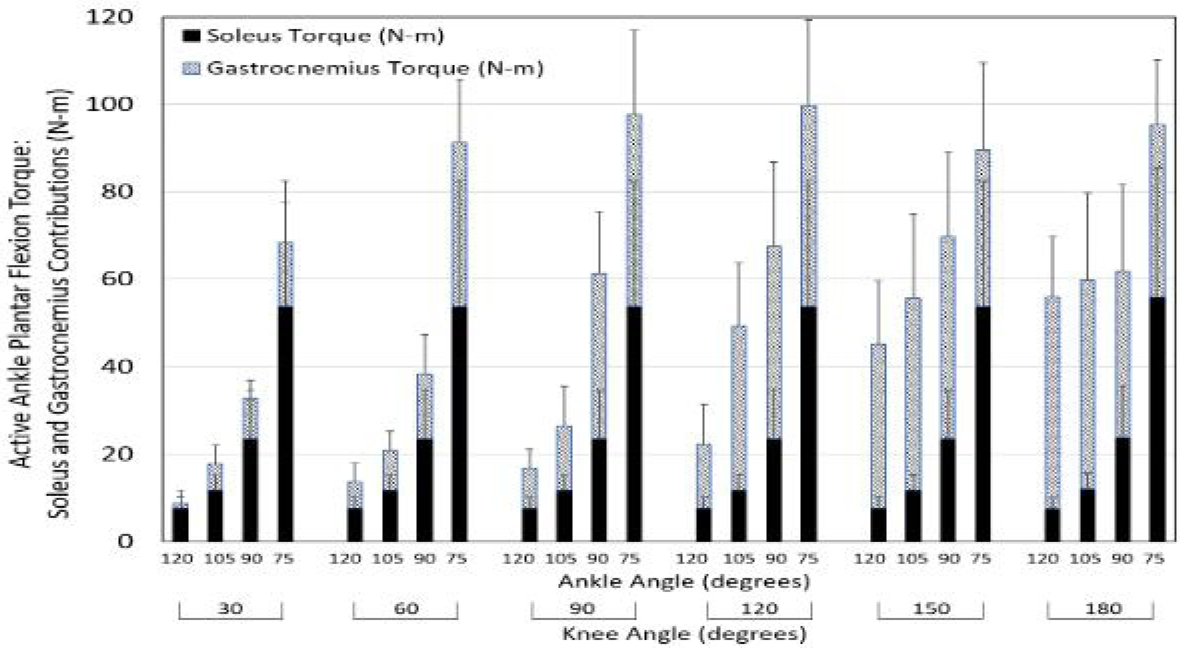

Figure 2: Absolute and relative gastrocnemius and soleus muscle contributions to isometric ankle plantar flexion torque as a function of ankle and knee angles.

As a function of knee angle, the change in average peak active PFT and the relative muscle contributions to this change depended on the ankle angle. The average peak active PFT increased with knee extension up to 90 degrees and then continued to increase with knee extension if the ankle was in a plantar flexed position, but tended to level off or decrease with knee extension if the ankle was neutral or dorsiflexed. Following a similar pattern, the gastrocnemius contribution to the average peak active PFT increased with knee extension up to 90 degrees and then continued to increase with knee extension if the ankle was in a plantar flexed position, but tended to level off or decrease with knee extension if the ankle was neutral or dorsiflexed (Figure 2). At a fixed 120° ankle angle, the gastrocnemius average active PFT increased from 0 to 39.4 Nm (± 21.5) and 81.5% (± 10.2) of the total PFT, as the knee moved from flexed to full extension. The soleus' absolute active PFT did not change during knee extension, however its relative contribution decreased from 100% to 18.4%. At a dorsiflexed position of 75°, extending the knee to 90° increased the gastrocnemius and soleus average active PFT values to 47.4 Nm (± 14.4) and 53.8 Nm (± 28.7), respectively. This translated into a 49.6% and 50.4% relative active contribution from the gastrocnemius and soleus, respectively. The gastrocnemius' relative contribution to active PFT decreased with further knee extension to 41.7 % (± 16.9) while the soleus' relative contribution increased to 58.3 %.

Discussion

The purposes of the present study were to identify the ankle-knee angle combinations that result in limited gastrocnemius ankle PFT producing capacity, and to characterize the relative contributions of the gastrocnemius and soleus muscles to ankle plantar flexion torque, as a function of ankle and knee angles. Characterizing the contributions of these muscles to PFT in humans has been attempted previously; however, other investigators have assumed the gastrocnemius PFT to be negligible or zero at a flexed knee of 90 or 60° [3,5,7] and estimated the PFT contributions of the gastrocnemius and soleus muscles at limited ankle-knee angle combinations. Making such an assumption can result in underestimation of the torque contribution of the gastrocnemius and the few ankle-knee angle combinations typically reported limit the utility of such studies. By testing the specific ankle-knee angle combinations considered in the present study, we were able identify the absolute and relative gastrocnemius and soleus muscle contributions to ankle PFT for a larger range of ankle-knee combinations than have been reported previously as well as the ankle-knee angle combinations that result in limited gastrocnemius ankle PFT producing capacity. The gastrocnemius has been shown to contribute significantly to ankle PFT at a 90˚ angle [2], but it has been unclear if the gastrocnemius can generate PFT for knee angles less than 90˚. The results from the current study clearly show that the gastrocnemius muscles in the endurance athletes tested in this study were able to generate PFT for all ankle-knee angles except the most plantar flexed ankle and flexed knee condition (Figure 2).

PFT trends from the present study agreed well with other results in the literature. Our findings that increases in ankle dorsiflexion and knee extension result in increases in PFT are consistent with findings in other studies [1,4,6,10-12]. The maximum average total PFT of 105.6 Nm from the current study agreed well with the values of 110 Nm and 103 Nm reported by others [1,13].

Gastrocnemius PFT contributions were 40% or higher in a fully extended knee position compared to a flexed knee position, for all ankle combinations. This is in line with Cresswell, et al.'s (1995) reported value of at least 40% from the gastrocnemius and 30% from the sol, considering the triceps surae accounts for 70% of the moment exerted by the plantar flexors [2]. However, the ankle was fixed at an 85˚ angle for all knee positions in their study, not optimizing the slackened state of the gastrocnemius muscle. Therefore, the gastrocnemius may have shown a larger contribution relative to the soleus. Interestingly, the gastrocnemius and soleus contributions were nearly equal where maximum peak PFT was attained (at a 75/90˚ ankle-knee combination), in the present study. The moment arm of the gastrocnemius at the knee and the Achilles tendon at the ankle change with joint motion. At the knee, the gastrocnemius moment arm can change from 2, 2.5, 3.25, 3.2, to 2.1 cm from 180˚ of knee extension to 60˚ of knee flexion, in increments of 30˚ [14]. These data were hand digitized from a study that tested 15 fresh cadavers and utilized the tendon excursion method, whereby an excursion of the tendon and change in angle are inputted to characterize the moment arm. At the ankle, the Achilles tendon moment arm can vary from 3.46 ± .59, 3.61 ± .54, 3.62 ± .50, 3.66 ± .70 cm from 75˚ ankle angle to 120˚ plantar flexion, in increments of 15˚ [15]. Moment arms can also vary depending on the methodology employed. These data were presented using the Tendon Excursion (TE) method. Fath, et al. (2010) reports that using a Center of Rotation Method (COR) leads to moment arm values 25% greater than those obtained using the TE method [15]. Both methods have their limitations. The moment arm assumptions presented in the current study are reasonable considering the deviations in moment arms in the literature. In the future, it would be of interest to ascertain whether gastrocnemius and soleus contributions to PFT as a function of ankle and knee angles depend on sport specific or habitual training. Both Maganaris (2003) and Herzog and Guimaraes (1991) provide evidence for adaptations in muscle contributions that would optimize habitual function rather than maximize contractile force generation [4,5,16].

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