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Title: Inter-individual similarities and variations in muscle forces acting on the ankle joint during gait

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Keywords: Ankle joint; Musculoskeletal model; Force generation; Gait analysis; Simulation

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Abstract: Muscle forces acting over the ankle joint play an important role in the forward progression of the body during gait. Yet despite the importance of ankle muscle forces, direct in-vivo measurements are neither possible nor practical. This makes musculoskeletal simulation useful as an indirect technique to quantify the muscle forces at work during locomotion. The purpose of this study was to: 1) identify the maximum peaks of individual ankle muscle forces during gait; 2) investigate the order over which the muscles are sorted based on their maximum peak force. Three-dimensional kinematics and ground reaction forces were measured during the gait of 10 healthy subjects, and the data so obtained were input into the musculoskeletal model distributed with the OpenSim software. In all 10 individuals we observed that the soleus muscle generated the greatest strength both in dynamic (1856.1N) and isometric (3549N) conditions, followed by the gastrocnemius in dynamic conditions (1232.5N). For all other muscles, however, the sequence looks different across subjects, so the k-means clustering method was used to obtain one main order over which the muscles' peak-forces are sorted. The results indicate a common theme, with some variations in the maximum peaks of ankle muscle force across subjects.

1. Cover Letter (Author Agreement)

COVER LETTER FOR SUBMISSION OF MANUSCRIPT

Dear Editor-in-Chief of
Gait and Posture

I am enclosing herewith a manuscript entitled "***Inter - individual similarities and variations in muscle forces acting on the ankle joint during gait***" for publication in **Gait and Posture** for possible evaluation.

With the submission of this manuscript, I would like to undertake the responsibility that the above mentioned manuscript has not been published totally or partly, accepted for publication or under editorial review for publication elsewhere. Submitted manuscript is an Original Article.

For the Editors, I would like to disclose the following information about the project:

The Corresponding author of this manuscript is Michalina Błażkiewicz and contribution of the authors as mentioned below with their responsibility in the research. Katarzyna Kaczmarczyk and Ida Wiszomirska collected and prepared data for analysis. Andrzej Wit, Michalina Błażkiewicz and Roozbeh Naemi made statistical analysis. Research Project is fully sponsored by NCN with grant number 2011/01/D/N27/05296.

In submitted manuscript entitled "***Inter - individual similarities and variations in muscle forces acting on the ankle joint during gait***" the most important and new finding was identify sequences of maximum muscle force peaks acting on ankle joint in dynamic and isometric conditions. This finding can be attributed to utilization of the effect of contraction-extension cycle, which has an impact on the strength and speed of movement during the investigation.

Please let me know of your decision at your earliest convenience.
With my best regards,
Sincerely yours,
Michalina Błażkiewicz, PhD

***2. Conflict of Interest Statement**

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***3. Response to Reviewers_2**

Answer to the reviewers

We thank reviewer for the valuable comments. Below are in-depth answers to the suggestions and queries.

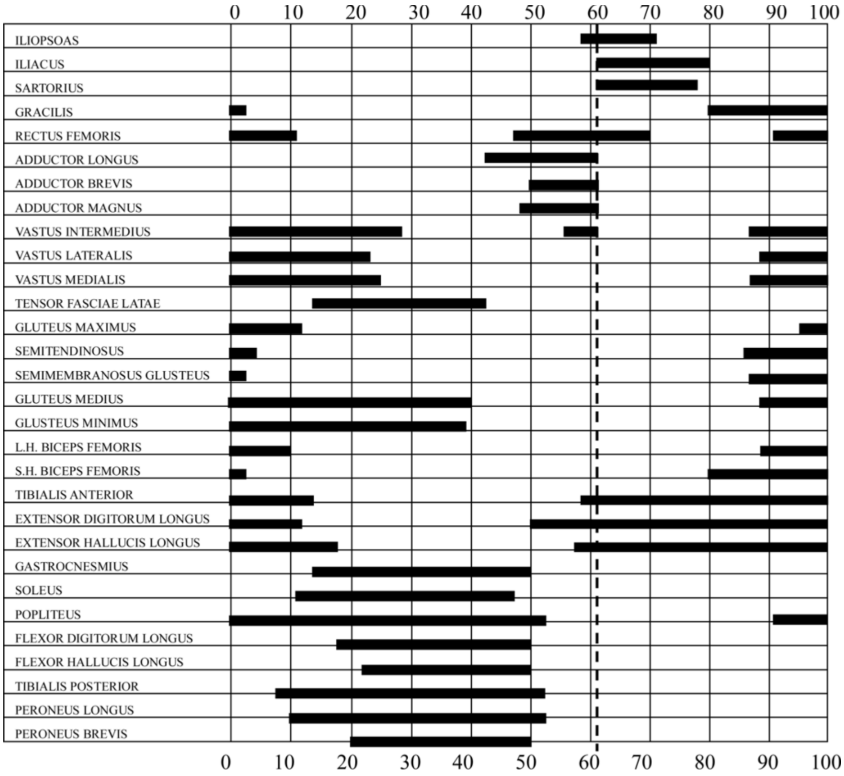
Reviewer #2:

The manuscript has improved, however, I still have some comments:

Page 2, L17-23: You state that during walking most lower limb muscles are active at the beginning and the end of swing phase. What about the m. gastrocnemius? This muscle is mainly active during stance phase? Muscles are also active during stance, not only swing. Could you explain the meaning of this sentence?

Thank you for this comment. The sentence referred to was worded as follows: "During walking, most of lower limb muscles are active at the beginning and the end of swing phase, which suggests that the main function of the muscles during walking is to accelerate and decelerate the leg. The rest of the work required for walking is contributed by passive force, through the joints and bones." (emphasis added).

We agree that the gastrocnemius muscle, like a number of others, is active mainly during the stance phase. This, for instance, is confirmed by the following diagram from the article Tao, W., Liu, T., Zheng, R., & Feng, H. (2012). Gait Analysis Using Wearable Sensors. *Sensors*, 12(2), 2255; *as well as the book* Perry, J. (1992). *Gait analysis: Normal and pathological function*, pp 163–165.

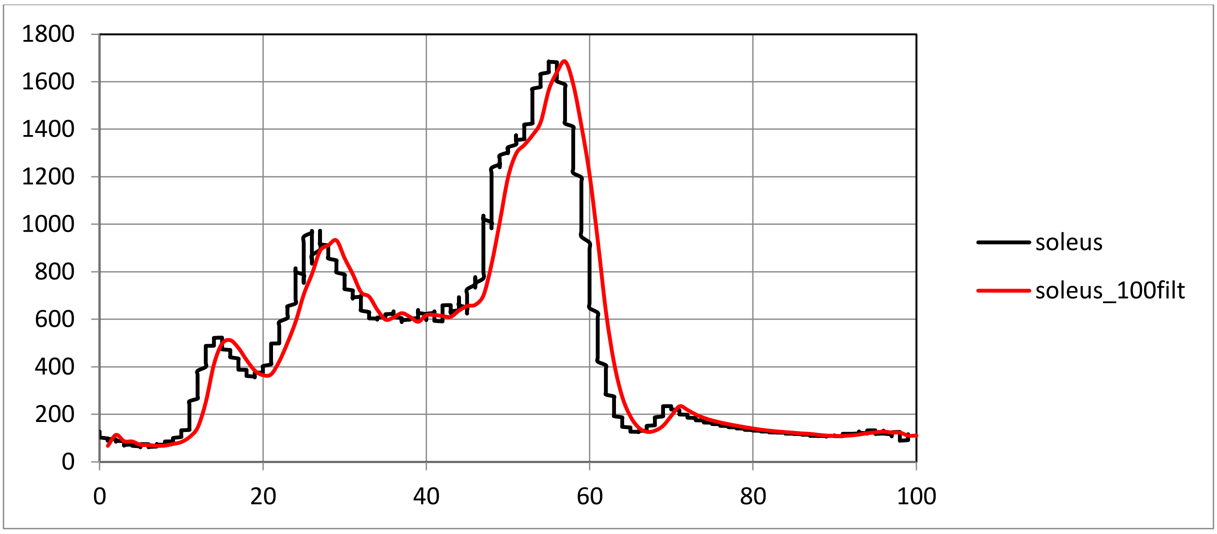


However, the purpose of this sentence as originally formulated was to stress that the main function of the muscles during walking is to accelerate and decelerate the leg, and this will largely be the task of the muscles active at the beginning and the end of swing phase. Be that as it may, we nevertheless came to the conclusion, after considering this comment and *reconsidering the entire introduction, that the sentence did not contribute directly to the main line of argumentation in the article and as such we have decided to delete it in this revised version.*

Page 3, L48: Here is a typo: change 'AAN' to 'ANN'.
Thank you, we have taken this remark into account and the manuscript has been changed appropriately.

Page 6, L15-17: Why did you filter your muscle force output? Was filtering of kinematic and kinetic data before using OpenSim not enough? Have you tried other filter option prior to using OpenSim and calculating the muscle force?

We did not try to use different filters for the input data for the OpenSim program, because most of the filters lead to a phase shift in the input signals, which change in the frequency function.
Overall, we strove to apply the procedures generally adopted for this software package. Your suggestion is thought-provoking but as such we have set such considerations aside for a subsequent publication.
As for why we filtered the muscle force output, an explanation is shown in the diagram below (showing data for one particular muscle, as the remainder are analogous).



Filtering of kinematic and kinetic data was nearly sufficient (the black line is clearly somewhat jagged), but because our work was based on maximal generated values, we wanted to further eliminate potential errors.
Following the doubts expressed by the reviewer, we compared the results and the filtering did not change the outcome: the maximal values were the same with and without filtering.
Your comment made us realize that potential doubts could arise in this respect, and as such we resolved to eliminate the sentence in question from this revised version of the draft.

Page 7, L27-31: I am still confused on the Statistics. In your comment you wrote you are comparing 4 groups, in the manuscript you only mention 3 groups. What are you comparing? And what is the aim of the statistics? Thus, what does a significant (or non-significant difference) tells us? Results on the Statistics show no significant difference in the current version. However, no discussion has changed regarding this. Actually, in the Discussion on page 12, L52 you are still mentioning a significant difference.

As we wrote before, we compared 4 groups. Group 1 – values of isometric muscle forces (Delp); Group 2 – maximal muscle peaks during gait cycle, Group 3 – Cluster 1, Group 4 – Cluster 2 (Table 1).
In the manuscript we have written: "In the last step, the Shapiro-Wilk test was applied to assess normal data distribution in all muscles groups, i.e. during isometric and dynamic conditions and clusters (Table 1). The non-parametric Kruskal-Wallis Test was used to detect differences between all groups. A significant p-value was set at 0.05 for all analysis." Here, "clusters" is understood to mean Groups 3 and 4.
The current version of the manuscript has been further adjusted to try to make certain that readers should not have any doubts in this respect.

As far as the Discussion section is concerned, admittedly we wrote as follows: "Although the use of k-means analysis of muscle forces during gait allowed a general framework sequence to be identified, this sequence proved to be significant different from that seen under isometric conditions".
However, this was misunderstood. As the result of the Kruskal–Wallis test shows, there are no differences between the groups analyzed in terms of the mean ranks of the groups, and this was indeed demonstrated, but in this passage of the Discussion section we are writing about something else: about how the ordering of the maximal peaks, when sorted from largest to smallest, varies completely from one group to another.

Page 8, L14-17: You have changed this part by changing the % value, however, I am still not convinced. This sentence tells me that isometric forces are lower than dynamic forces, but when I have a look in the Table it would be the other way round (dynamic forces > isometric forces). I am not sure if this sentence is misleading or if this information is not to be found in the Table and I am making wrong conclusions. Anyway, this should be clarified for a better understanding.

Summing up the values in Table 1, we obtain the following values: 11147N (Isometric), 6287N (Max peaks), 5509.9N (Cluster 1) and 7064N (Cluster 2). And so, Isometric > Dynamic. This is of course reasonable, even given the fact that for the simulation the isometric conditions are border conditions. Next, we do respond in the article to the question of what % of forces for static conditions is constituted by the sum of forces in dynamic conditions. By the following equation:

*X = (Max peaks)*100% / Isometric = (6287 / 1147)*100% = 56.4% (as reported in the article). In other words: Isometric * 56.4% = 6286.9*

Of course, we could also write by what percentage the sum of forces in dynamic conditions is smaller than in static conditions, and then the formula would be as follows:
$X = [(11147 – 6287) / 11147]*100\% = 43.6\%$

Page 9, L46-52: You are talking about static optimization here. I thought you have used the CMC approach?
Please excuse the mistake (incorrect translation of the term). The manuscript has been corrected with the abbreviation CMC.

Inter - individual similarities and variations in muscle forces acting on the ankle joint during gait

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Inter-~~-~~individual similarities and variations in muscle forces acting on the ankle joint during gait

Abstract

Muscle forces acting over the ankle joint play an important role in the forward progression of the body during gait. Yet d~~D~~espite the importance of ankle muscle forces, direct in-vivo measurements are neither possible nor practical. This ~~requires~~ makes ~~implementation of~~ musculoskeletal simulation useful as an indirect technique to quantify the muscle forces at work during locomotion. The purpose of this study was to: 1) ~~find~~ identify the maximum peaks of individual ankle muscle~~s~~ forces during gait; 2) investigate the order over which the muscles are sorted based on their maximum peak force. Three-dimensional kinematics and~~,~~ ground reaction forces were measured ~~during~~ during the gait of ~~walking of~~ 10 healthy subjects, and the~~.~~ ~~The obtained~~ data so obtained were ~~the~~ input into the musculoskeletal model distributed with the OpenSim software. ~~K-means clustering method was used to determine the order over which the muscles are sorted based on their maximum peak force.~~ In all 10 individuals we observed that the soleus muscle generated the greatest strength both in dynamic (1856.1N) and isometric (3549N) conditions, followed by the gastrocnemius in dynamic conditions (1232.5N). For all other muscles, however, the sequence looks different across subjects, so the~~.~~ ~~Using~~ k-means clustering method was used to obtain one main order over which the muscles’ peak-forces are sorted~~ was obtained~~. The results indicate~~d~~ a common theme, with some variations in the maximum peaks of ankle muscle force across subjects.

Keywords: Ankle joint; Musculoskeletal model; Force generation; Gait analysis; Simulation

Word count for the abstract: 199~~208~~; Word count for the main text: ~~2990~~2937

Number of Tables: 2; Number of Figures: 2

1. Introduction

Walking is a motor task requiring coordination of many muscles at work ~~working during~~ under dynamic conditions. During gait, each muscle produces its optimal force in synchrony with other muscles acting as synergists and antagonists on a particular joint. ~~On the other hand d~~During an isometric contraction, on the other hand, the muscles generate a maximal force which is wholly dependent on their length [1]. According to Zajac [2], the maximal isometric force is the force generated only by the sarcomeres when muscle is at 100% activation and the muscle fib~~r~~er length is equal to the muscle optimal fib~~r~~er length. ~~During walking, most of lower limb muscles are active at the beginning and the end of swing phase, which suggests that the main function of~~ the ~~muscles during walking is to accelerate and decelerate the leg. The rest of the work required for walking is contributed by passive force, through~~ the ~~joints and bones [3]~~. The foot and ankle, by virtue of their location, form a dynamic link between the body and the ground and are thus essential to upright locomotion. The ankle complex constantly adjusts itself during locomotion to enable a harmonious coupling between the body and the ground to achieve successful movement [3, 4]. The ankle joint muscles support the body, propel the center of mass forward during push-off phase of walking [5] and reduce energy losses due to heel strike [6, 7]. ~~But~~ However, the role of the individual ankle muscles during normal gait is controversial [8, 9]. Although the role of the plantarflexor in single support is generally accepted; the role of this muscle group in pre-swing ~~is~~ remains disputed. Force production by any muscle may alter the behavior at joints over which it crosses and may potentially affect~~s~~ motion at adjacent joints. White and Winter [10] suggest that ankle plantarflexors provide active ‘push-off’ in the transition from stance to swing. In contrast, Perry [8] indicates~~d~~ that rather than push-off these muscles prepare the limb for the swing phase. Since rehabilitation protocols are directed towards recovery of as much normal motion as possible, this lack of consensus ~~deem~~ is ~~to be~~ significant.

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Consequently, a ~~true~~ fuller understanding is needed of the inter-~~-~~individual differences and similarities in the roles ~~of~~ played by the ankle muscles and their contribution to the force and moments of the ankle during movement in healthy population~~ is essential~~.

Since muscle forces cannot be measured noninvasively [11], these quantities are determined using indirect methods of musculoskeletal simulation, combining gait analysis and ground-reaction-force measurements. The m~~M~~uscle force sharing problem deals with the determination of the internal forces acting on the musculoskeletal system using the known resultant inter-segmental forces and moments [10, 12]. The distribution problem for human joints is typically represented with an indeterminate set of system equations; that means there are more unknowns than there are ~~the~~ equations ~~that are~~ most often used for calculating the muscle, ligament and bone-to-bone forces acting in and around the joints. ~~The indeterminacy problem in biomechanics has been recently resolved using the min/max criterion for simulation of muscle recruitment in multiple muscle systems. The criterion was introduced and justified by comparison to two known criterion types: the polynomial criterion and the soft saturation criterion.~~

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~~For~~To assess ~~assessing the~~ similarities in data patterning, Artificial-Neural-Networks (ANN) and cluster analysis ~~was~~ were used for ~~the~~ classification of human movements on the basis of ~~the characteristics of~~ several variables [13]. Cluster analysis is the process of dividing data elements into classes so that the items in the same class are as similar as possible. Clustering has been previously used to categorize the gait of a number of subjects into healthy or pathological groups based on the joint angles [14, 15]. Furthermore ~~the~~ fuzzy k-means models have also been utilized in gait control systems in conjunction with functional electrical stimulation [16]. Overall, ~~the~~ musculoskeletal modeling and AN~~A~~N applications ~~of ANN is~~ are widely used for motion analysis [13, 17].

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Previous studies of ankle muscle forces distribution are mainly ~~either~~ based either on measuring the effects of major muscle groups on the center of pressure movement [18],~~;~~ or on determining the contribution of individual muscles to the net ankle power and ~~to~~ examining~~e~~ each muscle’s role in propulsion or support of the body during normal walking based on an EMG-to-force processing model [19, 20]. Using musculoskeletal model simulations, Blazkiewicz, Sundar [21] assessed the sequence of individual ankle muscle force~~s~~ peaks during isometric conditions in people with diabetes. ~~While,~~ Neptune, Kautz [5], in turn, analyzed the role of the plantarflexor muscles during gait, ~~and they~~ calculating~~ed~~ the degree to which these muscles contribute to propelling the body in the forward direction. However, ~~there is a scarcity of the~~ few studies ~~in which the~~ have assessed the order of maximal muscle force peaks ~~occurrence was assessed~~ during locomotion. Therefore, the objective of this study was ~~to~~: 1) to ~~find~~ identify the maximum peaks of individual ankle muscle~~s~~ forces during gait; 2) to investigate the order over which the muscles are sorted based on their maximum peak force. Such information ~~on the sequence of peak ankle muscles force during walking~~ ~~can~~ may provide a helpful design framework for such purposes ~~such~~ as the design of appropriate orthotic~~s~~ intervention to help resume~~ing~~ the natural activity of ankle muscles~~,~~ during rehabilitation. Moreover, this information may be useful for people with ankle muscle disorders, providing information about the differences in the generation of maximum muscle force~~s~~ capability during walking.

2. Materials and methods

2.1. Participants

~~10~~ Ten male healthy adults ~~with~~ (average age 24.5±6.6 years, height 181±8.7 cm and weight 75.9±7.3 kg) ~~were~~ participated in this study. The study was conducted according to the ethical principles of the Declaration of Helsinki. Prior to the start of the tests, participants were

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informed about the study procedures and the possibility of withdrawing from the experiment at any moment.~~ and expressed their consent to participate in the experiments.~~

2.2. Data collection

An eight-~~–~~camera Vicon system (Oxford, UK) with a sampling frequency of 100Hz was synchronized with two Kistler (Winterthur, CH) force platforms (1000Hz). A set of 34 markers ~~were ~~was placed on the body of each patient according to the standard Vicon Plug-~~I~~in-Gait~~ standards available within Vicon software~~. The participants were requested to walk at self-~~–~~selected speed along a walkway ~~of ~~approximately 10m in length. For each person, 3 valid trials performed without any random mistakes were collected. A valid trial was defined as ~~the ~~one in which subjects struck the force platform without adjusting their stride length.

2.3. Data analysis

The ~~obtained ~~kinematic~~s~~ and kinetic~~s~~ data from one representative trial for each subject~~s~~ were ~~an ~~input ~~-~~into the~~ musculoskeletal model distributed with~~ OpenSim software (Stanford, USA). ~~In the OpenSim software a ~~A generic musculoskeletal model with 19 degrees-of-freedom and 92 Hill-type muscle-tendon actuators was used to generate simulations. The head, arms and torso were modelled as a single rigid body which articulated with the pelvis via a ball-and-socket back joint. Each hip was modelled as a ball-and-socket joint, each knee as a hinge joint, each ankle, subtalar and metetersophalangeal joint as a revolute joint [22]. The model was scaled to match the anthropometry of each participant, using the anatomical landmarkers and functional joint centers as a reference. By solving an inverse kinematics problem, the joint angles of the musculoskeletal model that best reproduce the experimental kinematics of the subject were calculated. The i~~I~~nverse dynamics task was solved to determine net moments at each of the joints. Dynamic inconsistency between the measured ground-reaction-forces

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and the kinematics was resolved by applying small external forces and torques (i.e. residuals) to the torso and making adjustments to the model mass properties and kinematics [1]. Following a Residual-Reduction-Algorithm, muscle forces were computed using the Computed-Muscle-Control (CMC) tool. CMC is an optimization based control technique designed specifically for controlling dynamic models that are actuated by redundant sets of actuators whose force-~~-~~generating properties may be nonlinear and governed by differential equations [9]. ~~The outcomes from the CMC tool muscle forces curves were filtered with a 4th order Butterworth filter with a low-pass frequency of 20Hz.~~

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2.4. Analysis

For each subject, muscle force distribution curves and the maximum force value were calculated (Fig. 1) for each of the 12 muscles acting on the ankle joint during the gait cycle (8 ankle plantarflexors: the Flexor Digitorum, Flexor Hallucis, Gastrocnemius Lateral Head, Gastrocnemius Medial Head, Peronus Brevis, Peronus Longus, Soleus, Tibialis Posterior; and 4 ankle dorsiflexors: the Extensor Digitorum, Extensor Hallucis, Peroneus Tertius, Tibialis Anterior)~~ acting on the ankle joint during gait cycle were calculated~~. Thus, ~~for each individual twelve muscles~~ maximum values were obtained for each of the twelve individual muscles. Next, for each muscle, the average of ~~this~~ these values were compared with forces obtained in ~~the~~ isometric conditions, which were available ~~at~~ in the gait2392 model from OpenSim. These forces were also a border condition for the solution of the ~~static optimization~~CMC problem. The i~~I~~sometric muscle forces of Delp [23] were scaled upward based on joint moment-~~-~~angle data of healthy young males, as ~~done~~ performed by Carhart [24], reported in Yamaguchi [25]~~ paper~~. The maximum contraction forces were scaled to better reflect Anderson and Pandy's model and the joint torque-~~-~~angle relationships.

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In the next step~~,~~ the k-means clustering method was applied, using Statistica (StatSoft, PL), in order to ~~find~~ identify ~~the~~ groups ~~of~~ in terms of the ordering ~~the order~~ of ~~appearance of~~ maximum peaks of muscle force acting on the ankle joint during gait cycle~~ the k-mean clustering method was applied. To do this, Statistica (StatSoft, PL) was used~~. The procedure ~~follows~~ provides a way to classify a given data set through a certain number of clusters. The number of clusters (two) was chosen automatically by the software. The main idea is to define k-centroids (one for each cluster) in such a way that the centroids are placed as far from each other where the Euclidean distances between objects were calculated. The next step is to take each point belonging to a given data set and associate it to the nearest centroid. The program moves objects between those clusters with the goal to minimize variability within clusters and maximize variability between clusters. In the last step, the Shapiro-Wilk test was applied to assess normal data distribution in ~~all muscles~~ the four groups analyzed:~~ i.e.~~ during isometric and dynamic conditions ~~and~~ in the two clusters (Table 1). The n~~N~~on-parametric Kruskal-Wallis Test~~Friedman-test~~ was used ~~in order~~ to detect differences between all ~~3~~ groups. A significant ~~P~~p-value was set at 0.05 for all analysis.

3. Results

All the muscle~~s~~ forces acting on the ankle joint showed a similar trend over the gait cycle across participants. Figure 1 shows the individual muscle forces during gait for one representative subject.

Fig. 1. Individual muscle forces during gait for one ~~of the~~representative participants~~, where~~: A – forces generated by the soleus, gastrocnemius medial head, gastrocnemius lateral head; B – forces generated by the extensor digitorum, peroneus brevis; C – forces generated by the

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tibialis posterior, tibialis anterior, peroneus longus; D – forces generated by the extensor hallucis, flexor digitorum, flexor hallucis, peroneus tertius during the gait cycle.

During isometric conditions (Table 1), the strongest muscle group was the ~~gastrocnemius soleus~~triceps surae, reaching ~~which reaches~~ the value of 5790N. ~~While, in~~In the whole study group, an average maximum force peak of this muscle~~s~~ group during gait cycle ~~ranged~~ was 3464N. The sum of all the maximum muscle forces in isometric conditions was around ~~50~~56.4% of the corresponding value in ~~the~~ dynamic conditions. Moreover, the sorted order of ~~appearance of peaks of~~ the muscle forces peaks under dynamic conditions was not the same as under isometric conditions, and was moreover not consistent across the 10 subjects (Fig. 2).

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Fig. 2. All possible sequences of maximum muscle force contribution: A. under dynamic conditions for the study group, where ( ) is number of participants having the same order of the peak muscle forces;~~,~~ the ~~A~~ gray path is a major set in which individual muscles are presented for the study group; B. t~~T~~he sequence of maximum muscle force contribution under static conditions [23].

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~~It was~~Our model showed that ~~predicted~~found ~~that~~ in all 10 participants the soleus ~~shows~~reached the highest maximal muscle force value in both dynamic and static conditions. Under dynamic conditions, the ~~directly immediately after muscle soleus is~~ gastrocnemius medial head came immediately after the soleus. Third in terms of maximum force in dynamic conditions ~~in 8 participants~~ is the tibialis anterior (in 8 participants) ~~and~~ or the tibialis posterior (in 2 participants). The lowest value of maximum force peaks ~~we~~ was observed for the muscle flexor digitorum (7 participants), muscle flexor hallucis (2 participants) and extensor hallucis (1 person). For the remaining muscles crossing the ankle joint, the order ~~at~~ in which the peak muscle forces appeared was different. Therefore, in order to identify major sets in which individual muscles' maximum force peaks during gait cycle are present in a specific order, ~~the~~ k-means analysis was applied. As a result, two main sets were identified among the ~~for dividing~~ 10 subjects, ~~who have~~ exhibiting different orders of the maximum muscle force distribution ~~were found~~. The training error was: 2.8795. There were 5 individuals in each cluster. The means across first and second cluster arranged in order from highest to lowest are presented in Table 1.

Table 1 Maximal isometric muscle forces [23], average maximum muscle force during gait (dynamic conditions) and means across cluster for k-means~~s~~ clustering, where n – number of persons in each cluster.

The r~~R~~esults for the Shapiro-Wilk test indicate that all data across the muscles groups, i.e. during isometric conditions (p=0.003), dynamic conditions (p=0.007) and clusters (p=0.005, p=0.0056), had ~~different~~ non-normal distribution ~~than normal~~. Thus, to compare data, the non-parametric Kruskal-Wallis test ~~Friedman test~~ was performed. There was ~~a highly~~~~not~~ no statistically significant difference between groups, H(3, N=48)=4.~~,~~1028, p=0.2506. ~~Chi-Square. (N = 12, df = 3) = 22.7, p = 0.000.~~

4. Discussion

The overall objective of this study was to ~~find~~ identify the maximum peaks of muscle~~s~~ forces acting on the ankle joint during gait and to investigate the order over which the muscles are sorted based on their maximum peak force. The OpenSim software ~~package with a static optimization tool~~ was utilized to determine the individual muscle forces [1]. The ~~sStatic~~

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~~optimization~~Computed Muscle Control (CMC) method was used to solve the optimization problem at each instant during the gait cycle. Moreover, the average maximum peaks of 12 ~~ankle~~ individual ankle muscle forces calculated during dynamic conditions for 10 individuals were compared with muscle forces calculated during isometric contraction. Isometric muscle force peaks were taken from Delp's [19] study and scaled upward based on joint moment–~~-~~angle data of healthy young males, as ~~done by~~ in [22].

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In the current study, during the gait cycle the muscle tibialis anterior generated a~~s~~ maximum force peak of 911.8N (Table 1). The force-time graph generated by the extensor digitorum longus muscle has almost identical shape to the tibialis anterior [19], but has lower maximum force peak (430.4N). The peroneus longus (330.1N) is active during weight acceptance (10% of stride), which appears to stabilize the ankle and possibly works as a co-contraction to the tibialis anterior. The group of intrinsic muscles, like the flexor digitorum, has a maximum force peak (82.2N) at the beginning of the gait cycle. During midstance, the body's center of gravity reaches its highest point. ~~In~~ At this moment the ~~muscle~~ soleus muscle has a role in keeping the foot on the floor by eccentrically contracting [3] and it is also the point at which produces its maximum force contribution (Fig. 1). At the late stance phase of the gait cycle the body accelerates forward and nearly all the muscle work is generated by a shortening contraction of the ankle plantarflexors [3]. ~~Instead,~~ D~~d~~uring the swing phase, on the other hand, most of the lower limb muscles are inactive and the movement is like a pendulum, as ~~can be~~ seen in Figure 1. At the beginning of swing, the ankle dorsiflexors contract concentrically to allow the foot to clear off the ground and remain contracted throughout the whole swing phase. At the terminal swing phase, the goal is to decelerate the leg and prepare it for weight acceptance, ~~where~~ as ~~can be~~ seen in Figure 1. The contraction in the ankle dorsiflexors changes from concentric to isometric or eccentric [8].

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Our results show that in a dynamic condition the plantarflexors achieve a muscle force of 4348.46N, which is almost three times higher than that obtained from the dorsiflexors. The results are presented in Table 2 and compared against the isometric results presented by [26], who also described the percentage of force contributed by each of the muscles of the plantarflexors group (Table 2).

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Table 2 Percentage of each individual muscle compared to the entire group. Current study results compared to those reported by Oster [26].

Comparing the results obtained in this work and the results obtained by Oster [26], it was observed that ~~muscles~~ the gastrocnemius and flexor digitorum muscles had almost the same percentages of force contribution as compared to the whole group. However, the results of this study reveals ~~that~~ the muscle force contribution of the soleus to be 15% higher, that of the tibialis posterior 10% lower, that of the peroneus longus 5% higher, that of the peroneus brevis 3% higher and that of the flexor hallucis 2% lower as compared to the respective muscle contribution results presented in [23]. The ~~gastrocnemius and soleus~~ triceps surae muscle exhibited one long duration phase of activity throughout the single limb support period [27], ~~so that is the reason~~ making for ~~why it is~~ the highest muscle group force contribution, ~~which reaches~~ reaching an average maximum force peak of 5790N. The muscle tibialis anterior has its major activity at the end of swing to keep the foot in a dorsiflexed position [3, 28]. ~~It has been established that for the maintenance of human standing posture, ankle and hip strategies are used.~~ This latter paper attempts to identify whether the change of muscle force in the ankle joint can be used to distinguish some strategy (timing) of maximum muscle force peaks appearance during gait. It has also been established that the role of individual ankle muscles during normal gait is controversial [8, 10]. Muscles' activation

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across ~~the ~~subjects varies ~~is different, because there are some ~~due to certain factors influencing the EMG signal, including ~~the ~~tissue characteristics~~,~~ and physiological cross-talk~~,~~ ~~changes in the geometry between muscle belly and electrode site~~ [8]. In regular conditions, a healthy well-~~-~~organized muscle deactivates if it is not needed anymore. However, the relationship between muscle force and EMG signal is not always simple and linear, and so, as ~~was ~~reported in this paper, the maximum muscle capability based on normal walking is also different across the subjects. ~~In this paper we ~~We have shown that the order of maximum force peaks under dynamic conditions is not the same as under static conditions, and is not identical for all 10 participants, although some regularities were identified.~~.~~ ~~We ~~Our model showed~~predictedfound~~ that in the whole group of 10 individuals, the soleus achieved the highest peak in both dynamic and isometric conditions. Generally, the order of ~~appearance of~~ maximum peaks of ~~another ~~the other 10 muscle forces acting on the ankle joint during gait cycle was different for each subject. Therefore, in order to identify major sets in which individual muscles are present in a specific order, the k-means analysis was applied. As a result~~ of present paper~~, two main sets were identified for ~~dividing ~~classifying the 10 subjects ~~who have ~~with different orders of the maximum individual muscle force distribution ~~were predictedfound ~~(Table 1). Positioning averages across a cluster in order from the highest to the lowest enabled prediction of ~~predicting ~~the order of the maximum force peaks of ankle muscles. In addition, the results presented in this paper ~~realize ~~demonstrate that the maximum forces of individual ankle muscles during gait cycle are not the same for ~~the ~~all subjects and cannot be arranged in the same order (Fig. 2). This, in addition to the diverse age of the individuals, also can be attributed to utilization of the effect of the contraction-extension cycle, which has an impact on ~~the ~~strength and speed of movement during the investigation.

Although the use of k-means analysis ~~makes ~~of ~~the ~~muscle forces during gait allowed a certain general framework sequence of sorted peaks to be identified, this sequence ~~showed~~

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proved to be quite ~~significant~~ different from that seen under isometric conditions. ~~The results of this study can be useful for design of intelligent orthosis, or artificial muscles, and in conducting training or rehabilitation protocols design.~~

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5. Conclusions

In this study ~~it was~~ we observed that the sequences of maximum muscle force peaks acting on the ankle joint in dynamic and isometric conditions are different across individuals and within groups in dynamic conditions. Using the k-means clustering method, one main order over which the muscles peak-forces are sorted was obtained. The results indicated a common theme, with some variations in the maximum ~~-~~peaks of ankle muscle force across subjects. The results of this study may therefore be useful for design of intelligent orthosis, or artificial muscles, and in training or rehabilitation protocol design.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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Table 1

Maximal ~~I~~isometric muscle forces [19], average maximum and standard deviations of muscle forces during gait (dynamic conditions) and means across cluster for k-means clustering, where n – number of persons in each cluster.

Maximum ~~I~~isometric muscle forces [N] (Delp, 1990) [19]		Average maximum peak of muscle forces during gait [N]		Cluster 1 [N] (n = 5)		Cluster 2 [N] (n = 5)	
Soleus	3549	Soleus	1856.1 ± 252	Soleus	1488.6 ± 176	Soleus	2223.5 ± 327.3
Tib_post	1588	Med_gas	1232.5 ± 158.7	Med_gas	1202.3 ± 123	Med_gas	1262.8 ± 212.3
Med_gas	1558	Tib_ant	911.8 ± 131.5	Tib_ant	950.5 ± 121.1	Tib_ant	873 ± 139.3
Per_long	943	Tib_post	503 ± 178.5	Ext_dig	411.7 ± 150.2	Tib_post	691.6 ± 241.2
Tib_ant	905	Ext_dig	430.4 ± 107.2	Lat_gas	345.5 ± 100.8	Ext_dig	449 ± 56.1
Lat_gas	683	Lat_gas	375.5 ± 119.3	Tib_post	314.5 ± 123.5	Per_long	444.1 ± 124.4
Ext_dig	512	Per_long	330.1 ± 130	Per_long	216 ± 133.8	Lat_gas	405.6 ± 141
Per_brev	435	Per_brev	174.1 ± 72.1	Per_tert	156.9 ± 33.6	Per_brev	214.7 ± 105.7
Flex_hal	322	Per_tert	161.2 ± 28.5	Ext_hal	135.5 ± 23.9	Per_tert	165.5 ± 29.2
Flex_dig	310	Ext_hal	135.1 ± 21.2	Per_brev	133.5 ± 33.1	Ext_hal	134.7 ± 23.4
Per_tert	180	Flex_hal	95 ± 19.1	Flex_hal	81.2 ± 20.5	Flex_hal	108.8 ± 45.7
Ext_hal	162	Flex_dig	82.2 ± 15.3	Flex_dig	73.7 ± 12.3	Flex_dig	90.7 ± 34.8

Table 2

Percentage of each individual muscle compared to the entire group. ~~The~~ Current study results ~~from the Current study~~ compared to those reportede ~~results~~ by Oster [23].

Name of muscle	Individual muscle percentage of force contributed as compared to the group	
	Current study	(Oster, 2009) [23]
Soleus	40.38%	55.20%
Gastrocnemius	34.45%	37.50%
Tibialis Posterior	11.34%	1%
Flexor Hallucis	1.72%	3.30%
Flexor Digitorum	1.43%	1%
Peronus Longus	7.13%	1.50%
Peronus Brevis	3.54%	0.50%

7. Figure(s)

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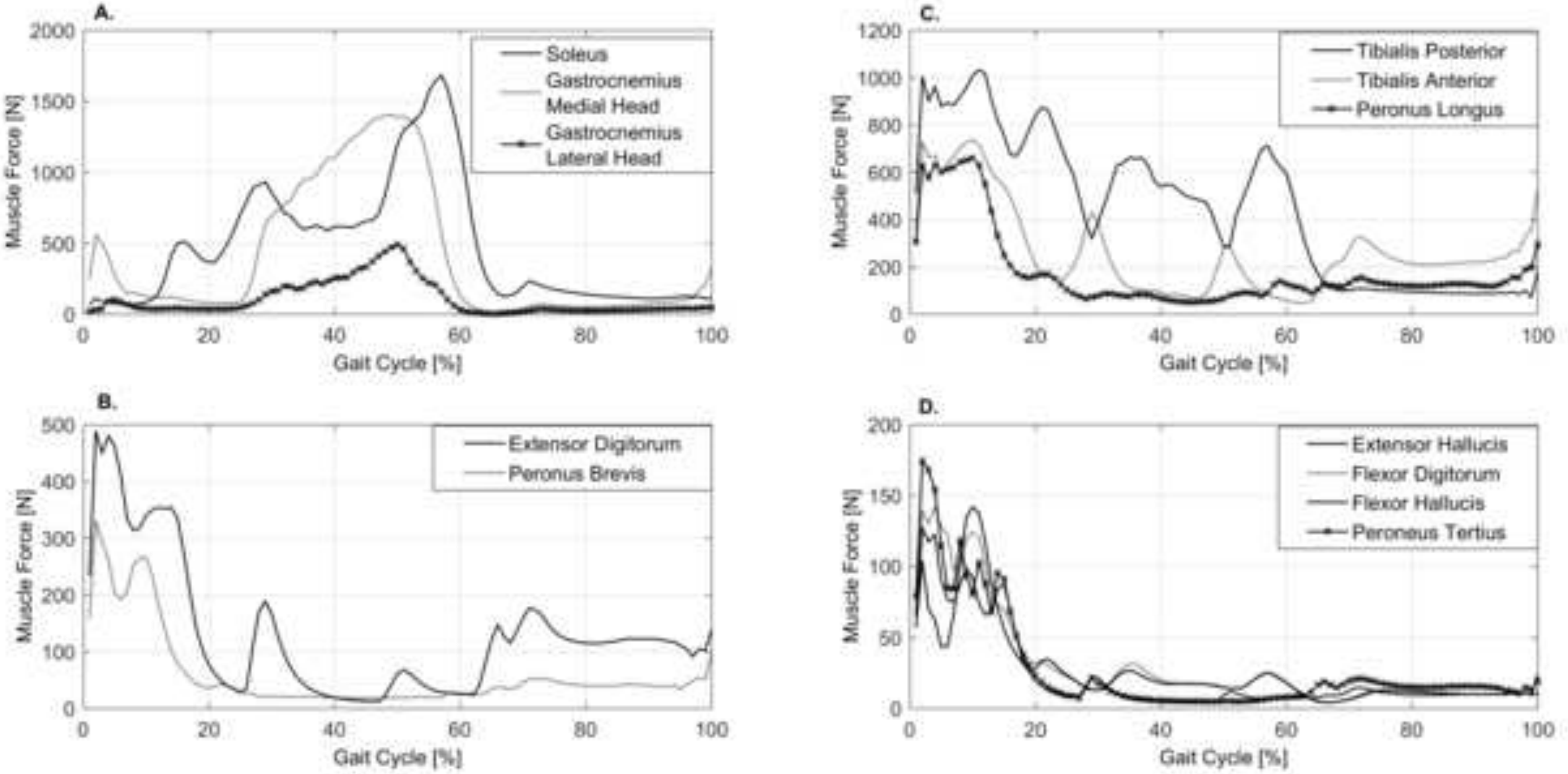

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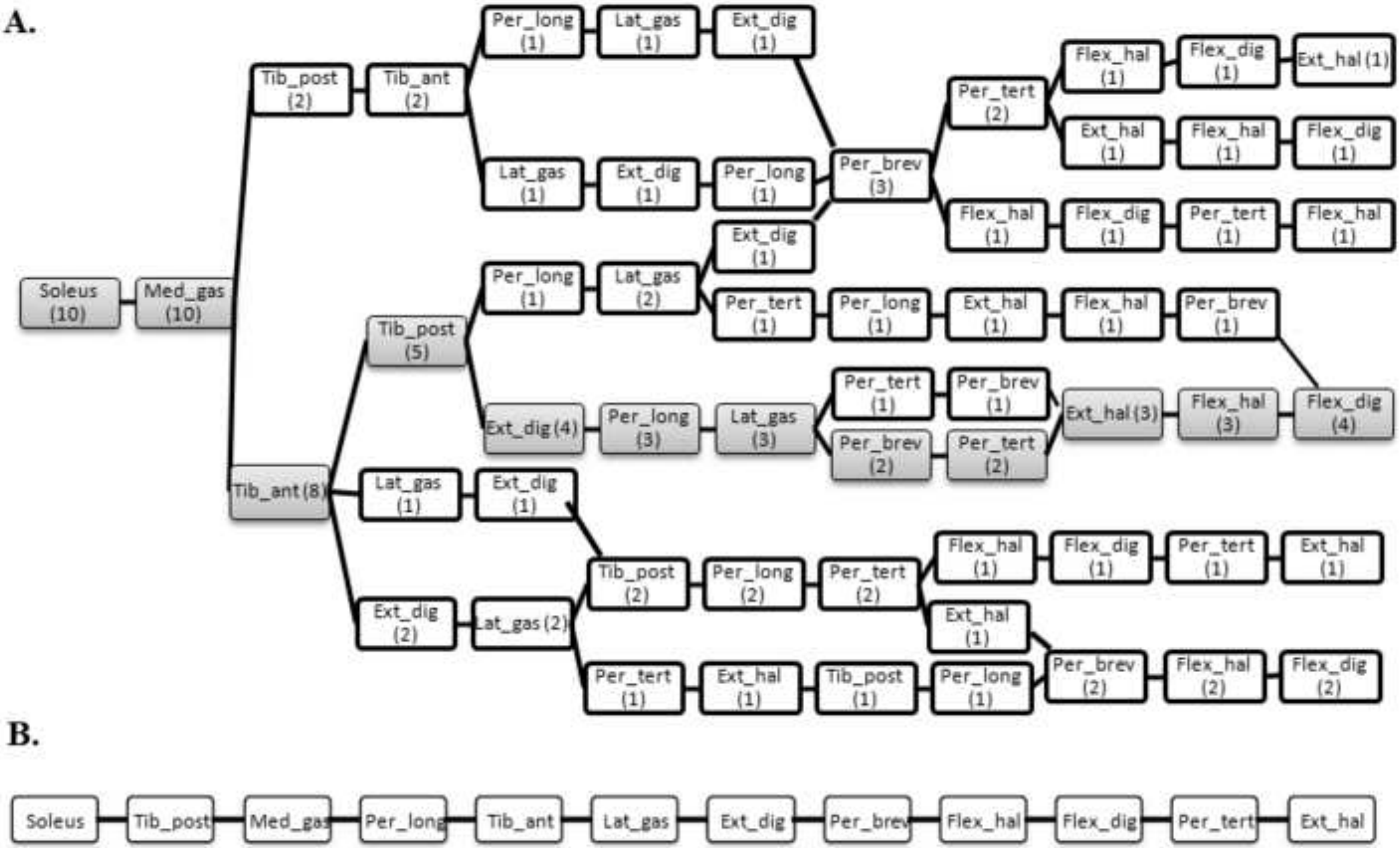

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Highlights

- Maximum-peaks of individual ankle muscles forces during gait is found.
- Variation in maximum-peaks of ankle muscle force across subjects was demonstrated.
- The order over which the muscles are sorted was determined.