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

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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. Introduction

Walking is a motor task requiring coordination of many muscles at work 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. 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 fiber length is equal to the muscle optimal fiber length. 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]. 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 remains disputed. Force production by any muscle may alter the behavior at joints over which it crosses and may potentially affect 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 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 is significant. Consequently, a fuller understanding is needed of the inter-individual differences and similarities in the roles played by the ankle muscles and their contribution to the force and moments of the ankle during movement in healthy population.

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 muscle 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 equations most often used for calculating the muscle, ligament and bone-to-bone forces acting in and around the

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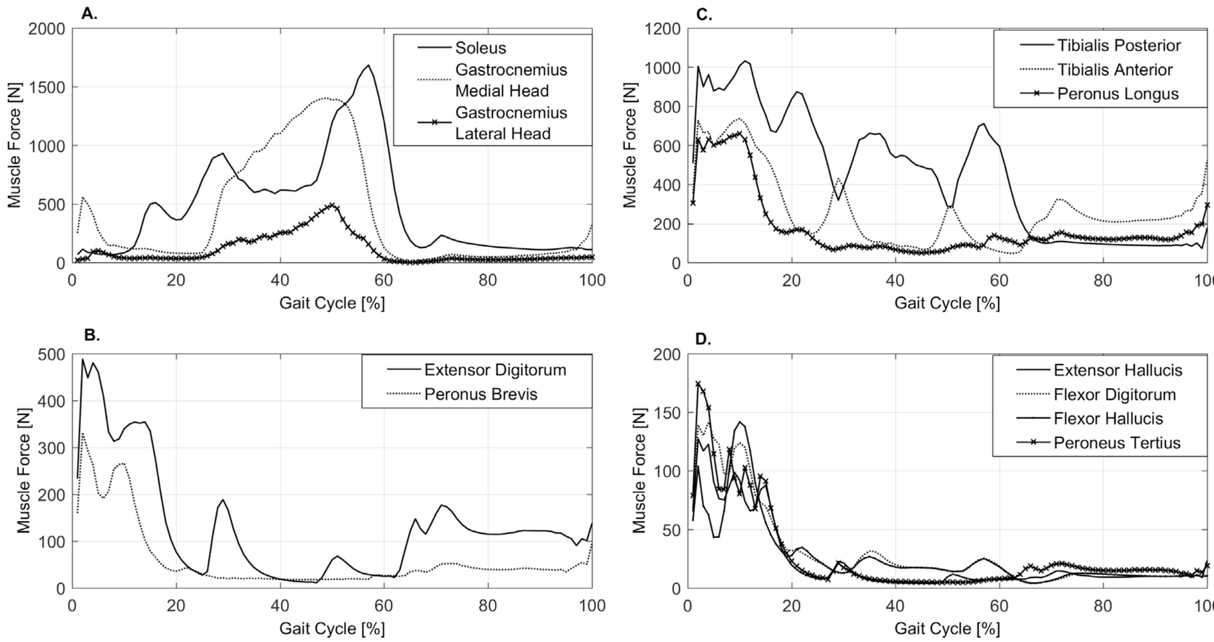

Fig. 1. Individual muscle forces during gait for one representative participant: A – forces generated by the soleus, gastrocnemius medial head, gastrocnemius lateral head; B – forces generated by the extensor digitorum, peroneus brevis; C – forces generated by the tibialis posterior, tibialis anterior, peroneus longus; D − forces generated by the extensor hallucis, flexor digitorum, flexor hallucis, peroneus tertius during the gait cycle.

joints. To assess similarities in data patterning, Artificial-Neural-Networks (ANN) and cluster analysis were used for classification of human movements on the basis 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 fuzzy k-means models have also been utilized in gait control systems in conjunction with functional electrical stimulation [16]. Overall, musculoskeletal modeling and ANN applications are widely used for motion analysis [13,17].

Previous studies of ankle muscle forces distribution are mainly 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 examining 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 peaks during isometric conditions in people with diabetes. Neptune, Kautz [5], in turn, analyzed the role of the plantarflexor muscles during gait, calculating the degree to which these muscles contribute to propelling the body in the forward direction. However, few studies have assessed the order of maximal muscle force peaks during locomotion. Therefore, the objective of this study was: 1) to identify the maximum peaks of individual ankle muscle forces during gait; 2) to investigate the order over which the muscles are sorted based on their maximum peak force. Such information may provide a helpful design framework for such purposes as the design of appropriate orthotic intervention to help resume 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 capability during walking.

2. Materials and methods

2.1. Participants

Ten male healthy adults (average age 24.5 ± 6.6 years, height 181 ± 8.7 cm and weight 75.9 ± 7.3 kg) 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 informed about the study procedures and the possibility of withdrawing from the experiment at any moment.

2.2. Data collection

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

2.3. Data analysis

The kinematic and kinetic data from one representative trial for each subject were input into the OpenSim software (Stanford, USA). A generic musculoskeletal model with 19°-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 inverse dynamics task was solved to