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Partitioning ground reaction forces for multi-segment foot joint kinetics

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ABSTRACT

Background: Kinematic multi-segment foot models have been increasingly used to study foot function. The addition of kinetics to these models may enhance their utility; however, this been hindered by limitations in measuring ground reaction forces (GRFs) under individual foot segments.
Purpose: To determine the accuracy of partitioning segment GRFs from a single force platform on foot joint kinetics.
Methods: Two potential partitioning methods were applied to a previously published three-segment kinetic foot model. The first method calculated joint kinetics only when the center of pressure crossed anterior to a joint (CPcross). The second method utilized a virtual pressure mat and a proportionality assumption to partition GRFs from the force platform (PRESS). Accuracy was assessed by comparing joint moments and powers obtained from each partitioning method to those obtained from a dual force plate approach that isolated forces under two segments at a time (2Plate). Thirteen healthy pediatric subjects walked in a controlled manner so as to isolate the kinetics acting at the metatarsophalangeal (MTP) joint and, subsequently, the midtarsal joint.
Results: The PRESS method was generally more accurate than the CPcross method, and both methods were more accurate at the midtarsal joint than at the MTP joint. At the MTP joint, sagittal plane moment peaks, power peaks, and work done were slightly overestimated, more so by CPcross than PRESS. At the midtarsal joint, sagittal plane moments were captured well by PRESS, while CPcross missed the early portion of the moment, but both methods captured power profiles fairly accurately.
Significance: Analysis of kinetics in multi-segment foot models may provide insight into foot function, pathologies, and interventions. Partitioning accuracy and generalizability is promising for analysis of the midtarsal joints but has limitations at the MTP joint.

1. Introduction

In clinical gait analysis and human movement research, traditional single segment foot models are increasingly being replaced by models that subdivide the foot into several segments (e.g. [1–4]). To date, these multi-segment foot (MSF) models have primarily been confined to the analysis of joint angles. Expanding these kinematic-only models to also allow for kinetics analysis may provide additional insights into foot function [5–9], but requires several additional parameters. In addition to segment orientations, inverse dynamics based kinetics calculations also rely on identification of joint centers of rotation, estimation of segment inertial properties, and measurements of ground reaction forces (GRFs) under each segment. Of these, measuring segment GRFs is perhaps the most difficult hurdle from a technological standpoint, as commercial devices capable of measuring both segment vertical and shear forces are not yet commonplace [10], and the use of multiple adjacent force plates [5,11,12] requires targeted walking which may not be clinically feasible.

A method that can accurately partition the GRFs from a single force plate is attractive because it would allow MSF joint kinetics to be calculated from commonly employed equipment already found in gait and movement analysis clinics and laboratories. Two potential methods of GRF partitioning have been developed previously. The first method quantifies joint kinetics from a single force plate only when the location of the center-of-pressure (CoP) passes anterior to the joint, i.e. the entire GRF is applied to adjacent segments sequentially. This technique has only been used to examine kinetics of the metatarsophalangeal joints [e.g. 13–15], but could theoretically also be applied to other joints in the foot, such as the midtarsal joint. The second method employs an additional pressure mat secured to the top of the force plate. The segment vertical forces from the pressure mat are then used to help partition the shear forces from the force plate using an assumption of proportionality [7,16]. The accuracy of this latter method on segment GRFs alone has been evaluated [9,17,18], but neither method has been

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validated in terms of application to inverse dynamics based MSF joint kinetics.

The purpose of the present study was to assess the accuracy of potential GRF partitioning methods on the calculation of MSF joint kinetics (i.e. moments, powers, and work), using a previously published kinetic multi-segment foot model [5,19]. This was accomplished by comparing estimates obtained from the partitioning methods to those from a multiple force plate approach that isolated forces under two segments at a time. By studying the potential errors inherent in these methods, we hope to better understand their validity and applicability. The ability to calculate foot joint kinetics from a single force platform would provide researchers and clinicians with a new tool with which to study foot muscle function, better understand foot pathologies, and evaluate potential treatment interventions.

2. Methods

2.1. Participants

We re-analyzed data that were previously collected [5,17,19], consisting of 13 healthy pediatric participants(9 M/4F; age 13.1 ± 3.1; height 156 ± 18 cm, weight 51 ± 18 kg). Four of the original 17 subjects were excluded due to concerns over foot placement accuracy. All participants were volunteers and signed consent forms approved by the local Institutional Review Board.

2.2. Protocol

The employed marker set, associated multi-segment foot model, and collection protocol have all been previously documented [5,19]. Details that are particularly relevant to this study are described briefly here. Nineteen total reflective markers were first placed on the right leg and foot of each participant. The associated three segment foot model consists of hindfoot, mid/forefoot (hereafter referred to as simply the 'forefoot' segment), and hallux segments separated by midtarsal and metatarsophalangeal (MTP) joints. The midtarsal joint center was defined as the midpoint between markers placed on the navicular and cuboid bones, while the MTP joint was estimated at the center of the first metatarsal head by projecting a dorsal marker vertically downward. Each participant next walked at a self-selected speed across a floor containing two force plates (AMTI inc., Watertown MA USA, model OR6-7-1000) that were positioned directly adjacent to each other (separated by a 2 mm gap). Two sets of trials (Fig. 1) were collected using a controlled three-step approach. In the MTP trials, the third step was intended to position the entire hallux segment so that it contacted the anterior force plate, while the rest of the foot contacted the posterior force plate. These trials were used to analyze the kinetics of the MTP joint. In the midtarsal trials, the hallux and forefoot segments contacted the anterior force plate, while the hindfoot was isolated on the posterior plate. These trials were used to analyze the kinetics of the midtarsal joint. Participants were instructed to walk as normally as possible, while the investigators adjusted the starting positions to ensure appropriate foot contact. Obtaining three successful trials typically required 15–30 trials, and proper foot contacts were verified visually by two video cameras located on either sides of the force plates.

2.3. Data analysis

Marker trajectories were collected at 120 Hz (Vicon 612 system, Oxford England UK) and filtered at 6 Hz, while GRF data was collected at 1560 Hz, filtered at 50 Hz, and threshold cutoff at 1N. MTP and midtarsal joint moments and powers were calculated in Visual 3D software (C-Motion, inc., Germantown MD USA) by assigning the separate GRFs from the adjacent force plates to their corresponding segments; i.e. to the forefoot and hallux in the MTP trials, and to the hindfoot and forefoot in the midtarsal trials. The results were considered the gold standard and referred to as "2Plate" in comparisons. The inverse dynamics computations were then performed two additional times for each trial, representing GRF segment partitioning methods (Fig. 1). Only the GRF input changed among methods.

In the first partitioning method (called "CPcross"), the two GRF vectors from the individual force plates were mathematically summed to simulate a single GRF vector from a single force plate, and the summed GRF was applied to a segment based on the anterior-posterior location of the CoP (in laboratory coordinates). For instance, in the MTP joint trials, the GRF was applied to the forefoot from initial contact until the CoP passed anterior to the MTP joint, at which point it was applied entirely to the hallux segment [14]. Similarly, in the midtarsal trials, the GRF was applied first to the hindfoot, followed by the forefoot once the CoP passed the midtarsal joint.

In the second method (called "PRESS"), the data from the two force plates were synthesized to simulate signals that would be obtained from a single force plate in conjunction with a pressure mat. First, the vertical forces and CoPs for the two segments of interest were taken from the individual force plates, mimicking the same data outputs from a pressure mat. The GRF vectors from the two plates were summed to simulate a single plate, and the segment shear forces and free moments were then estimated from the summed GRF by assuming they were distributed in the same proportions as the vertical forces [7,16]:

$$f_{APi} = \left(\frac{f_{Vi}}{F_V}\right)F_{AP}$$

$$f_{MLi} = \left(\frac{f_{Vi}}{F_V}\right)F_{ML}$$

$$m_i = \left(\frac{f_{Vi}}{F_V}\right)M$$

Where f_i represents the segment force and F represents the total (summed) force, whether vertical (V) anteroposterior (AP) or mediolateral (ML). For example, f_{vi} represents the vertical force under segment i (extracted from an individual force plate), and F_v represents the summed force from both plates. Similarly, m_i represents the segment free moment and M the summed free moment.

Midtarsal and MTP joint moments and powers for the PRESS and CPcross methods were compared to the 2Plate method to assess accuracy. Joint moment vectors were expressed as internal moments in the proximal segment's coordinate system. Sagittal and transverse plane moments were analyzed for the MTP joint, while all three planes of midtarsal moments were included. Joint power was calculated as the scalar dot product of the joint moment and joint angular velocity. Moments and powers were both normalized by body mass. Comparisons were primarily made descriptively, using mean time series waveforms. These were created by first time-normalizing a representative trial from each subject to 100% of stance, then taking the mean across subjects at each time point. Following initial waveform inspection, a few selected metrics were chosen to provide numerical context. These included peak sagittal plane MTP moments and peak MTP powers, sagittal plane MTP and midtarsal angular impulse (integral of moment), and MTP and midtarsal total negative and positive mechanical work (integral of power). In addition, the timing of various relevant events was recorded. These included the times when the CoP crossed anterior to the midtarsal and MTP joints, as well as the onset times when GRF was first and last recorded under each segment (from the 2Plate data). These were expressed as percentages of stance phase (see Table 1). All metrics are presented as means ± standard deviations across subjects.