

GROUND REACTION FORCE MEASUREMENTS FOR MULTI-SEGMENT FOOT MODELS

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INTRODUCTION

Kinematic multi-segment foot models have been increasingly used in clinical gait analysis and human movement research. The addition of kinetics to multi-segment foot modeling, however, has been hampered by measurement difficulties. MacWilliams et al [1], for example, created a complex eight-segment foot model, measuring ground reaction forces (GRFs) using both a force platform and a pressure mat. Shear forces (f_{AP} , f_{ML}) and free moments (m) under each foot segment (i) were estimated by assuming that they were distributed proportionally to the vertical forces (f_v):

$$\begin{aligned} f_{APi} &= (f_{vi} / F_v) * F_{AP} \\ f_{MLi} &= (f_{vi} / F_v) * F_{ML} \\ m_i &= (f_{vi} / F_v) * M \end{aligned} \quad (\text{Method 1})$$

In addition to relying upon an unproven proportionality theory, this method also cannot account for the possibility of opposing shear forces on separate foot segments (e.g. substantial collapse of the medial longitudinal arch in mid-stance or whole foot rotation). Giacomozzi and Macellari [2] suggested accounting for foot rotation by partitioning the overall free moment among the various segments and adjusting the shear values:

$$\begin{aligned} f_{APi} &= (f_{vi} / F_v) * F_{AP} - f_{Mi} * \sin(\alpha_i) \times \\ f_{MLi} &= (f_{vi} / F_v) * F_{ML} + f_{Mi} * \cos(\alpha_i) \times \\ m_i &= d_i \times f_{Mi} \end{aligned} \quad (\text{Method 2})$$

And $f_{Mi} = f_{vi} * (M / f_{vi} * d_i)$

Where d_i is the vector from the force plate center of pressure to each sensor, and α_i is the angle between d_i and the x-axis.

This method, however, is mathematically problematic, as $\sum f_i \neq F$. Not surprisingly, therefore, Yavuz et al.[3] found larger errors using method 2 than method 1 to predict peak shear stresses over the forefoot during gait. Both methods, though, showed RMS errors greater than 85 kPa.

The purposes of the present study were to: 1) measure the shear forces and free moments under a 3 segment foot model during normal gait, and 2)

further evaluate the accuracy of the shear force proportionality assumption (using method 1).

METHODS

17 normal pediatric subjects (9M, 8F), representing a range of ages (7-18, mean 12.6) and foot sizes, were tested. Only the right foot was tested. Subjects first walked at a self-selected speed across a floor containing 2 adjacent AMTI OR6-7-100 force platforms. A minimum of 3 trials with full foot/plate contacts were collected. Next, the subject walked using a three-step targeting method, so that the rearfoot contacted one plate while the forefoot (and toes) contacted the adjacent plate. Foot placement was verified by two video cameras located on either side of the plate division. Finally, the same method was repeated, but with the hallux and toes on one plate and the rest of the foot on the adjacent plate. Subjects were instructed to walk as normally as possible and the starting position was adjusted until the appropriate placement, with a near normal gait pattern, was achieved. Trials were collected until at least three were identified with accurate foot placement (for each joint line).

Ground reaction force data was collected at 1560 Hz, low-pass filtered at 100 Hz, and threshold cutoff at 5N. Data processing was performed using Visual 3D software (C-motion, Inc). For the targeted trials, overall ground reaction forces were calculated by combining the outputs of the two force platforms to create a single virtual platform. Method 1 was then used to estimate the shear forces and moments on each platform from the virtual platform. All forces were then time-normalized to a complete gait cycle. A representative trial for each subject and each joint condition was chosen as the one with the smallest total RMS differences between its associated virtual GRFs and the mean GRFs from the initial, non-targeted trials. The representative trials were used to calculate a mean over all subjects (see Figure).

RESULTS AND DISCUSSION

With few exceptions, the measured and estimated forces were consistent, so that the group means are a reasonable representation (although not indicative of the full range of errors and particularly peak errors). RMS errors ranged from approximately 1% BW up to 6% BW in some cases, and were usually highest between the foot and toes in the AP direction.

Both ML and AP shear forces showed some small opposing actions between the rearfoot and forefoot in mid-stance. In early and mid-stance, the braking force by the rearfoot was underestimated, and a considerable portion of this force was falsely attributing to the forefoot. The greatest opposing actions occurred between the foot and the toe in the AP direction, as the toes ‘flattened’ in terminal stance. Method 1 markedly overestimated the propulsive contribution of the hallux and toes, and consequently underestimated the propulsive force of the forefoot. Besides periods of opposing shear forces, there are errors throughout the gait cycle, likely due to inaccuracies in the proportionality theory. Ironically, this theory was proposed for use in multi-segment foot models, yet it by definition assumes that the foot is a single, uniformly deforming, isotropic plantar surface.

The main limitation to this study is that the GRFs are based on targeted walking. However, the virtual GRFs from the chosen trials generally matched the initial non-targeting trials, consistent with Grabiner et al [4], who previously showed good agreement between targeted and non-targeted GRFs. Our methodology also limited force analysis to two segments at a time, but the salient information from each of these analyses occurs at time periods where the third segment is not a prominent factor. In fact, superposition of these curves may be possible so that all three separate segment forces can be estimated in a general sense.

In conclusion, this study has shown that although overall estimation errors can be relatively small, important information on segment function is lost using proportionality assumption methods to estimate shear forces.

(Disclaimer: The opinions expressed in this abstract are those of the authors and do not necessarily reflect the views of the National Institute for Occupational Safety and Health.)

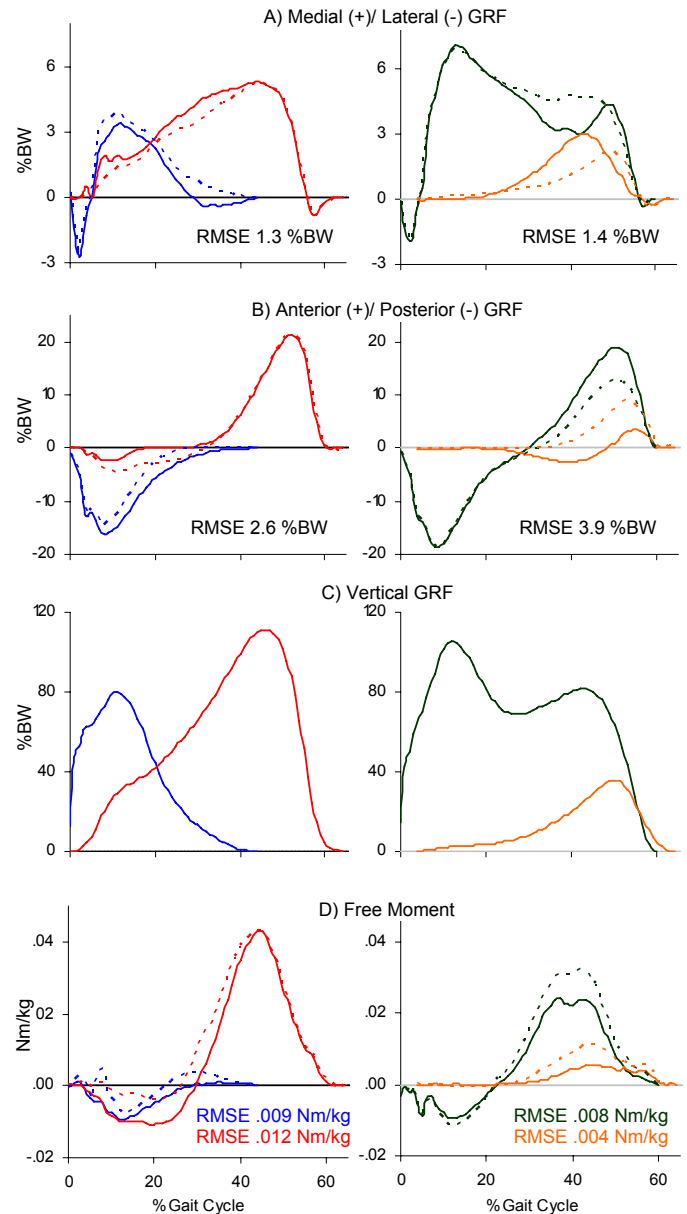


Figure. Mean measured and estimated, time normalized ground reaction forces under a 3-segment foot model during normal gait (N=17).

— Rearfoot — Forefoot — Foot — Toes
 - - - Rearfoot Est - - - Forefoot Est - - - Foot Est - - - Toes Est

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