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The neuromuscular demands of toe walking: A forward dynamics simulation analysis

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Abstract

Toe walking is a gait deviation with multiple etiologies and often associated with premature and prolonged ankle plantar flexor electromyographic activity. The goal of this study was to use a detailed musculoskeletal model and forward dynamical simulations that emulate able-bodied toe and heel-toe walking to understand why, despite an increase in muscle activity in the ankle plantar flexors during toe walking, the internal ankle joint moment decreases relative to heel-toe walking. The simulations were analyzed to assess the force generating capacity of the plantar flexors by examining each muscle's contractile state (i.e., the muscle fiber length, velocity and activation). Consistent with experimental measurements, the simulation data showed that despite a 122% increase in soleus muscle activity and a 76% increase in gastrocnemius activity, the peak internal ankle moment in late stance decreased. The decrease was attributed to non-optimal contractile conditions for the plantar flexors (primarily the force–length relationship) that reduced their ability to generate force. As a result, greater muscle activity is needed during toe walking to produce a given muscle force level. In addition, toe walking requires greater sustained plantar flexor force and moment generation during stance. Thus, even though toe walking requires lower peak plantar flexor forces that might suggest a compensatory advantage for those with plantar flexor weakness, greater neuromuscular demand is placed on those muscles. Therefore, medical decisions concerning whether to reduce equinus should consider not only the impact on the ankle moment, but also the expected change to the plantar flexor's force generating capacity.

Keywords: Musculoskeletal modeling; Equinus gait; Intrinsic muscle properties; Muscle force

1. Introduction

Toe walking is a gait deviation with multiple etiologies ranging from cerebral palsy to traumatic brain injury. It is often associated with premature and prolonged ankle plantar flexor electromyographic (EMG) activity (e.g., Colborne et al., 1994; Kalen et al., 1986), spasticity (e.g., Cahan et al., 1989; Perry et al., 1974) and contractures (e.g., Kelly et al., 1997; Stricker and Angulo, 1998). The increased plantar flexion posture can compromise walking stability and often results in decreased stride length and walking speed (Cahan et al., 1989; Davids et al., 1999; Hicks et al., 1988).

Recently, it has been proposed that toe walking provides a compensatory advantage over conventional heel-toe walking (Hampton et al., 2003; Kerrigan et al., 2000). Kerrigan et al. (2000) performed an inverse dynamics-based analysis of able-bodied subjects during heel-toe and toe walking and observed a significant decrease in the peak internal ankle plantar flexor moment and power generated in terminal stance and pre-swing during toe walking. They concluded that toe walking may provide a benefit for those with upper

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motor neuron injury and distal lower extremity weakness by requiring lower ankle plantar flexor strength. Similarly, Hampton et al. (2003) performed a quasi-static analysis of the foot and tibia using data recorded from able-bodied subjects emulating toe walking postures of individuals with cerebral palsy. Their results showed that the increased equinus posture results in reduced plantar flexor force requirements. The reduced plantar flexor force (primarily from the gastrocnemius and soleus) was attributed to the closer proximity of the resultant ground reaction force vector to the ankle joint center with greater angles of plantar flexion. Similar to Kerrigan et al. (2000), they concluded that equinus walking is most likely a compensatory strategy for plantar flexor weakness.

While these studies noted a reduction in the plantar flexor force requirements during toe walking, Perry et al. (2003) demonstrated using fine wire electromyography that plantar flexor muscle activity during toe walking is greatly increased in late stance despite a reduced net plantar flexor moment. They hypothesized that the dichotomy between increased muscle activity and decreased joint moment was due to a reduction in force generating capacity of the ankle muscles because of greater plantar flexion angles during toe walking. Thus, although the peak plantar flexor force required during toe walking may be lower, the neuromuscular demand placed on the plantar flexors appears to be greater.

The isometric moment generation of the plantar flexors decreases with increasing plantar flexion angles (e.g., Gravel et al., 1988; Miyamoto and Oda, 2003; Nistor et al., 1982; Sale et al., 1982), despite an increase in the moment arm of the gastrocnemius and soleus about the ankle joint with increasing plantar flexion angles (Rugg et al., 1990). The decrease in moment output is attributed to the muscles operating at non-optimal lengths on the muscle fiber force–length relationship. Thus, the increased ankle plantar flexion angle during toe walking likely reduces the force-generating capacity of the muscles. In addition, walking contains periods of both shortening and lengthening contractions of the plantar flexor muscles. Therefore, the muscle force generating capacity during walking could be impacted by both changes in fiber length as well as velocity. The poor contractile conditions associated with increased plantar flexion angles was recently highlighted in a modeling and simulation study showing that as ankle plantar flexion increases with walking speed, the force generating capacity of the plantar flexors becomes increasingly impaired (Neptune and Sasaki, 2005).

The goal of the present study was to explicitly test the hypothesis that greater angles of plantar flexion during toe walking are associated with a lower force generating capacity of the ankle plantar flexors compared to the normal posture in heel-toe gait. A detailed musculoskeletal model and forward dynamical simulations of able-bodied toe and heel-toe walking were developed to assess the force generating capacity of the plantar flexors by examining each muscle's contractile state. Specifically, we examined the muscle fiber length, velocity and activation relationships during toe and heel-toe walking to assess whether toe walking requires greater neuromuscular effort.

2. Methods

2.1. Forward dynamical simulations

Forward dynamical simulations of toe and heel-toe walking were generated using a previously described musculoskeletal modeling and dynamic optimization framework (e.g., Neptune et al., 2004) to analyze the contractile state and force production of the ankle plantar flexors. The sagittal-plane biped musculoskeletal model was developed using SIMM (MusculoGraphics Inc., Evanston, IL, USA) and the model's equations of motion were generated using SD/FAST (PTC, Needham, MA, USA). The equations of motion were then incorporated into simulation code generated by the Dynamics Pipeline (MusculoGraphics Inc., Evanston, IL, USA). Details of the musculoskeletal model and dynamic optimization that were used to produce the forward dynamical simulations emulating experimentally collected kinesiological data of able-bodied heel-toe and toe walking are described below.

2.2. Musculoskeletal model

The musculoskeletal model included a trunk (head, arms and torso combined as one segment) and right and left legs (each leg containing a femur, tibia, patella and foot) (Fig. 1). Degrees-of-freedom for the model included hip, knee and ankle flexion/extension for both legs, and trunk horizontal and vertical translation and anterior/posterior tilting. The knee flexion angle was used to prescribe two translational degrees-of-freedom of the knee joint (Yamaguchi and Zajac, 1989) and the position and orientation of the patella relative to the femur (Delp et al., 1990). The foot consisted of three segments: hindfoot, forefoot and toes. Flexion/extension was allowed between the hindfoot and forefoot and the forefoot and toes. Passive stiffness torques were applied at these joints so that realistic displacements were achieved during mid-stance. The model had a total of 13 degrees-of-freedom. Thirty visco-elastic elements were attached to the bottom of each foot segment to model the contact between the foot and ground. Details of the foot–ground contact model and parameter values are provided in Neptune et al. (2000).