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A unified deformable (UD) segment model for quantifying total power of anatomical and prosthetic below-knee structures during stance in gait

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ABSTRACT

Anatomically-relevant (AR) biomechanical models are traditionally used to quantify joint powers and segmental energies of lower extremity structures during gait. While AR models contain a series of rigid body segments linked together via mechanical joints, prosthetic below-knee structures are often deformable objects without a definable ankle joint. Consequently, the application of AR models for the study of prosthetic limbs has been problematic. The purpose of this study was to develop and validate a *unified deformable* (UD) segment model for quantifying the total power of below-knee structures. Estimates of total below-knee power derived via the UD segment model were compared to those derived via an AR model during stance in gait of eleven healthy subjects. The UD segment model achieved similar results to the AR model. Differences in peak power, total positive work, and total negative work were $1.91 \pm 0.31\%$, $3.97 \pm 0.49\%$, and $1.39 \pm 0.33\%$, relative to the AR model estimates. The main advantage of the UD segment model is that it does not require the definition of an ankle joint or foot structures. Therefore, this technique may be valuable for facilitating direct comparisons between anatomical and disparate prosthetic below-knee structures in future studies.

1. Introduction

In the field of biomechanics and human gait analysis, estimates of mechanical power and energy provide valuable insights into the mechanisms that contribute to the overall performance of locomotion (Winter, 2005). As these measures have been critical for the identification of neuromuscular deficits in persons with pathologies such as stroke, and cerebral palsy (Bennett et al., 2005; Detrembleur et al., 2003; Van den Hecke et al., 2007), much interest has existed in the use of mechanical power and energy for understanding the functions of prosthetic below-knee components (Barr et al., 1992; Ehara et al., 1993; Fey et al., 2011; Gitter et al., 1991; Postema et al., 1997; Silverman et al., 2008; Su et al., 2007; Winter and Sienko, 1988). However, as with many biomechanical analyses, the accuracy and validity of joint power and segmental energy estimates are sensitive to the underlying assumptions of the biomechanical models. Therefore, the capacity to objectively examine prosthetic mechanics is influenced by a model's ability to accurately represent the structural design of the system (Kent and Franklyn-Miller, 2011; Sawers and Hahn, 2011).

In the study of anatomical limbs, biomechanical models play critical roles in quantifying the rate of energy added or removed from the body through net muscular activity (e.g., joint power analysis) or transferred from one segment to another (e.g., segmental power analysis) (Winter, 2005). Traditionally, anatomically-relevant (AR) models contain a series of rigid body segments linked together via mechanical joints. Over the years, the AR joint and segment models have evolved to more fully capture the structural behavior of the body, and ultimately improved upon the estimates of joint and segmental powers. For example, joint models have evolved from a sagittal plane one degree of freedom (DOF) model (Elftman, 1939), to a triplanar 3 rotational DOF model (Apkarian et al., 1989), and eventually to a 6 DOF model (Buczek et al., 1994) that yields a mathematically complete estimate of joint power. Similarly, the foot segment model has evolved from a single segment rigid body model (Robertson and Winter, 1980), to a distally deformable foot model (Siegel et al., 1996) that more accurately depicts the foot's mechanics as it interacts with the ground during stance in gait.

Despite the evolution, AR models are currently limited to systems that contain anatomically congruent structures, such as segments and joints. Using rigid body mechanics and inverse

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dynamics analyses, joint kinetics are estimated using ground reaction forces, segment kinematics, and segment anthropometrics (Caldwell and Forrester, 1992; Winter, 2005; Sawers and Hahn, 2010). However, select prosthetic below-knee limbs may act as a deformable object and may not contain a definable ankle joint. Consequently, non-articulating prosthetic designs hinder the ability to accurately measure AR joint and/or segmental powers (Prince et al., 1994; Geil et al., 2000; Sawers and Hahn, 2010).

To address the limitations of AR models, Prince and colleagues presented a technique to compute the distal segmental power at the 'rigid part of the prosthetic leg', using an energy-based approach to quantify the total power of deformable structures attached distally to the 'prosthetic leg' (Prince et al., 1994). This technique has been used to study commercially-available prosthetic limbs (Prince et al., 1998), and more recently, prosthetic prototypes (Morgenroth et al., 2011; Segal et al., in press; Zelik et al., 2011). However, the method for computing the deformable segment power is based on the rate of change in segmental energy, which requires the estimates of segment kinematics and anthropometrics using rigid body mechanics. More recently, Sawers and Hahn (2011) used a helical axis method to identify the functional joint center of non-articulating prosthetic designs. Though, the helical axis estimate requires kinematics of two rigid body segments. Thus, despite attempts to modify existing AR models to accommodate non-articulating prostheses, there is currently a lack of generalized method to objectively compare structurally different below-knee systems. Therefore, the purpose of this study was to propose and evaluate a *unified deformable* (UD) segment model for quantifying the 'total power' due to the combined actions of *all structures distal to the knee*.

2. Theoretical development

2.1. AR model

In anatomical limbs, ankle joint and distal foot structures (intrinsic foot musculature and plantar soft tissue and ligaments) collectively function to add or remove mechanical energy from the body. Then, the total power of these below-knee structures derived via an AR model (P_{AR}) can be found by summing the total ankle joint power (P_{ank}) using a 6 DOF joint model (Buczek et al., 1994), and distal foot segmental power (P_{ftd}) using a deformable foot model (Siegel et al., 1996):

$$P_{AR} = P_{ank} + P_{ftd} \tag{1}$$

P_{ank} (Eq. (2)) is the summation of power due to the dot product of the ankle joint force (F_{jt}) and the joint translational velocity (Δv) and power due to the dot product of the ankle joint moment (M_{jt}) and the joint angular velocity (ω_{jt}). F_{jt} and M_{jt} are obtained through traditional inverse dynamic calculations, combining the estimates of force platform data (ground reaction force and free moment), foot segment kinematics and anthropometrics. Δv and ω_{jt} signify the relative velocity differences between the shank and foot segments:

$$P_{ank} = F_{jt}\,\Delta v + M_{jt}\,\omega_{jt} \tag{2}$$

During stance, structures like the plantar soft tissues or ligaments can deform, and the metatarsal-phalangeal joints can flex or extend. As a result, there is an associated movement of the center of pressure (COP) with respect to the foot segment (Siegel et al., 1993). This COP displacement, defined by the vector (r_{ft_cop}) from the center of mass (COM) of the foot to the COP location, is indicative of the 'net deformation' of distal foot structures under load. By accounting for the translational and rotational motions of the foot during stance, the total deformation velocity of the distal foot (v_{ftd}) can be quantified (Eq. (3)), where v_{cm_ft} is the translational velocity of the COM of the foot, and ω_{ft} is the angular velocity of the foot:

$$v_{ftd} = v_{cm\_ft} + (\omega_{ft} x r_{ft\_cop}) \tag{3}$$

It is important to note that the kinematics of the foot segment (v_{cm_ft} and ω_{ft}) are estimated through rigid body mechanics, while the distal endpoint kinematics (v_{ftd}) signify the deformable behavior of the foot. Thus, the deformable foot model differs from a traditional rigid body segment model, as it contains a *proximal rigid component* with an in-series *distal deformable component*. Then, by combining the measures of v_{ftd} and kinetic data from the force platform, the distal foot segmental power can be quantified. Specifically, P_{ftd} (Eq. (4)) is the summation of power due to the dot product of the ground reaction force (F_{grf}) and v_{ftd}, and power due to the dot product of the free moment (M_{free}—which only exists in the global transverse plane) and the ω_{ft} (Siegel et al., 1996):

$$P_{ftd} = F_{grf}\,v_{ftd} + M_{free}\,\omega_{ft} \tag{4}$$

2.2. Unified deformable (UD) segment model

While P_{AR} provides a valid estimate for anatomical below-knee structures, the AR model is not applicable to prosthetic systems that have no analog for the ankle joint and foot structures. To overcome this limitation, all structures distal to the knee are modeled as a *unified deformable* (UD) segment that can generate, store, dissipate, and/or return energy. Analogous to the deformable foot model (Siegel et al., 1996), the UD segment is a hybrid segment composed of a *proximal rigid component* with an in-series *distal deformable component*. Similar to traditional rigid segment models, the *proximal rigid component* is used to establish the UD segment coordinate system and to estimate the segment's kinematics. Distally, function of the deformable component is captured through the displacement of the COP with respect to the UD segment's COM (r_{UD_cop}). By accounting for the translational and rotational velocities of the *proximal rigid component* of the UD segment, the total deformation velocity of the distal component (v_{UDd}) can be quantified (Eq. (5)), where v_{cm_UD} is the translational velocity of the UD segment COM and ω_{UD} is the UD segment angular velocity:

$$v_{UDd} = v_{cm\_UD} + (\omega_{UD} x r_{UD\_cop}) \tag{5}$$

Then, by combining UD segment kinematics and kinetic data from the force platform, the total distal power of the UD segment (P_{UD}) can be quantified. Specifically, P_{UD} (Eq. (6)) is the summation of power due to the dot product of the F_{grf} and v_{UDd}, and power due to the dot product of the M_{free} and ω_{UD}:

$$P_{UD} = F_{grf}\,v_{UDd} + M_{free}\,\omega_{UD} \tag{6}$$

Altogether, the UD segment model is designed as a generalized model to quantify the total power of below-knee structures, without the need to define an ankle joint or foot segment. To test the validity of the UD segment model, estimates of P_{UD} were compared to those of P_{AR} in normal gait. By demonstrating that these two estimates achieve similar results in a system containing ankle joint and foot structures, it is assumed the validity of P_{UD} estimates holds across a wide range of physical characteristics found in prosthetic below-knee systems (e.g., articulating and/or non-articulating components).

3. Methods

Eleven healthy subjects (5 males and 6 females) participated in a fully-instrumented gait analysis. Subject characteristics are listed in Table 1. They were