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Multivariable static ankle mechanical impedance with relaxed muscles

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ABSTRACT

Quantitative characterization of ankle mechanical impedance is important to understand how the ankle supports lower-extremity functions during interaction with the environment. This paper reports a novel procedure to characterize static multivariable ankle mechanical impedance. An experimental protocol using a wearable therapeutic robot, Anklebot, enabled reliable measurement of torque and angle data in multiple degrees of freedom simultaneously, a combination of inversion–eversion and dorsiflexion–plantarflexion. The measured multivariable torque–angle relation was represented as a vector field, and approximated using a method based on thin-plate spline smoothing with generalized cross validation. The vector field enabled assessment of several important characteristics of static ankle mechanical impedance, which are not available from prior single degree of freedom studies: the directional variation of ankle mechanical impedance, the extent to which the ankle behaves as a spring, and evidence of uniquely neural contributions. The method was validated by testing a simple physical "mock-up" consisting of passive elements. Experiments with young unimpaired subjects quantified the behavior of the maximally relaxed human ankle, showing that ankle mechanical impedance is spring-like but strongly direction-dependent, being weakest in inversion. Remarkably, the analysis was sufficiently sensitive to detect a subtle but statistically significant deviation from spring-like behavior if subjects were not fully relaxed. This method may provide new insight about the function of the ankle, both unimpaired and after biomechanical or neurological injury.

1. Introduction

While all joints in the kinematic chain between foot and trunk (ankle, knee, and hip) participate in lower-extremity functions, the contribution of the ankle is significant (DeVita et al., 2007). Ankle mechanical impedance plays an important role in natural interaction of the lower extremity with the environment, including postural stabilization during standing as well as propulsion, energy-absorption, and lower limb joint coordination during locomotion. Sinkjaer et al. (1998) measured intrinsic and reflex contributions to the stiffness of the ankle dorsiflexors. Lamontagne et al. (1997) studied the viscoelastic behavior of the plantarflexors at rest. Other research measured the relaxed stiffness of the ankle plantarflexors and/or dorsiflexors to compare unimpaired and neurologically impaired subjects (Singer et al., 2002; Harlaar et al., 2000; Rydahl and Brouwer, 2004; Chung et al., 2004; Kobayashi et al., 2010). Stochastic system identification methods were used by Hunter and Kearney (1982), Kearney and Hunter (1982), and Weiss et al. (1986a,b). Other work measured ankle stiffness during quiet standing (Winter et al., 2001; Morasso and Sanguineti, 2002; Loram and Lakie 2002a,b) and "quasi-stiffness" during locomotion (Davis and DeLuca 1996; Palmer, 2002; Hansen et al., 2004). Mizrahi et al. (1990) studied the passive dynamics of the ankle in sudden inversion. Saripalli and Wilson (2005) examined the variation of frontal plane ankle stiffness under different weight bearing conditions. Zinder et al. (2007) measured inversion/eversion ankle stiffness using a medial/lateral swaying cradle. All of the above studies considered only a single degree of freedom (DOF) either in the sagittal plane (dorsiflexion–plantarflexion (DP)) or the frontal plane (inversion–eversion (IE)). Recently, Roy et al. (2009) measured static ankle impedance for IE and DP directions separately. However, we found no prior work characterizing ankle mechanical impedance in coupled multiple DOFs.

Unlike the ankle, multivariable upper-extremity mechanical impedance has been studied extensively. Multivariable analysis allows a distinction between the contributions of neural feedback and intrinsic muscle properties to static mechanical impedance (Hogan, 1985; Mussa-Ivaldi et al., 1985; Lacquaniti et al., 1993). As the ankle also has multiple DOFs and single DOF movements are rare under natural conditions, characterization of multivariable ankle mechanical impedance in multiple DOFs promises deeper understanding of its roles in lower-extremity function.

In electrical engineering usage impedance maps current onto voltage but the analogy between electrical and mechanical

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