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A method to combine numerical optimization and EMG data for the estimation of joint moments under dynamic conditions

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Abstract

To solve the problem of muscle redundancy at the level of opposing muscle groups, an alternative method to inverse dynamics must be employed. Considering the advantages of existing alternatives, the present study was aimed to compute knee joint moments under dynamic conditions using electromyographic (EMG) signals combined with non-linear constrained optimization in a single routine. The associated mathematical problems accounted for muscle behavior in an attempt to obtain accurate predictions of the resultant moment as well as physiologically realistic estimates of agonist and antagonist moments. The experiment protocol comprised (1) isometric trials to determine the most effective EMG processing for the prediction of the resultant moment and (2) stepping-in-place trials for the calculation of joint moments from processed EMG under dynamic conditions. Quantitative comparisons of the model predictions with the output of a biological-based model, showed that the proposed method (1) produced the most accurate estimates of the resultant moment and (2) avoided possible inconsistencies by enforcing appropriate constraints. As a possible solution for solving the redundancy problem under dynamic conditions, the proposed optimization formulation also led to realistic predictions of agonist and antagonist moments.

Keywords: Optimization; Electromyography; Co-contraction; Inverse dynamics; Stepping-in-place

1. Introduction

The assessment of joint moments for the quantification of co-contraction (Falconer and Winter, 1985; Winter, 1990) remains a significant challenge. Such data represent expressive information for rehabilitation applications (Kellis, 1998), and could provide a powerful means for exploring the control of joint stability (De Serres and Milner, 1991; Milner, 2002), body posture (Winter et al., 1998, 2001) and movement (Latash, 1992). From a mechanical point of view, the estimation of the moments produced by opposing muscle groups requires implementation of an alternative method to the inverse dynamics approach. Indeed, the problem of redundancy inherent in the musculoskeletal system (i.e., more muscles than degrees of freedom) yields not enough equilibrium equations to uniquely calculate individual moments (An et al., 1995; Happee, 1994).

As a solution for either opposing muscle groups or individual muscles, numerical optimization methods have been used under static and dynamic conditions (Crowninshield and Brand, 1981; Happee, 1994; Pedotti et al., 1978; Seireg and Arvikar, 1973; Stokes and Gardner-Morse, 2001). Using these approaches, forces or moments are obtained by minimizing an appropriate criterion (e.g., sum of normalized forces squared: Pedotti et al., 1978; sum of muscle stresses cubed: Crowninshield and Brand, 1981) subject to constraints (e.g., equilibrium equations: Pedotti et al., 1978; physiological bounds: Happee, 1994). Nevertheless, Buchanan and Shreeve (1996) and Challis and Kerwin (1993) and Challis (1997) highlighted that the solutions from optimization methods could be unsuitable (physiologically unrealistic), specially because they fail to consider an indicator of muscle activity (Cholewicki et al., 1995; Gagnon et al., 2001).

A convincing alternative approach should associate numerical optimization with the use of

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electromyographic (EMG) signals, which provide information on the level of muscle activity. Under isometric contractions the development of powerful algorithms for computing efforts from EMG (Buchanan et al., 1993; Laursen et al., 1998; van Dieen and Visser, 1999) is more conveniently performed because the relationship between force and EMG can be considered as linear (Hof, 1997; Onishi et al., 2000). Conversely, the use of EMG as an input variable under dynamic conditions involves major limitations because of muscle dynamics and possible signal artefacts (Kellis, 1998; Rainoldi et al., 2000). To solve this problem, Olney and Winter (1985) introduced a powerful solution, accounting for the moment–angle and the moment–velocity effects. Their influence was incorporated into the model with two biological-based constants depending, respectively, upon angular changes and angular velocity (for details see Olney and Winter, 1985, p.10). The associated experiment protocol comprised two sessions to (1) calculate coefficients to establish the relationship between EMG and the resultant moment under isometric contractions and (2) compute the joint moments during gait according to the coefficients calculated during the first session. Nevertheless, the solutions provided by this method should be adjusted by enforcing sub-weights, in order to perfectly balance the resultant joint moment (Cholewicki and McGill, 1994). Whether including this optimization algorithm as a separate routine can fully satisfy the equilibrium equations associated with the resultant moment (Cholewicki et al., 1995; Gagnon et al., 2001), the agonist and antagonist moments may remain physiologically unrealistic. Moreover with such methods, the associated criterion does not exploit the possibility of reflecting "a mechanism via which the human body recruits muscles to produce a joint moment" (Challis, 1997, p. 254).

So, the purpose of the present study was to develop a procedure associating the two alternatives presented above in a single routine for solving the redundancy problem at the level of knee muscle groups under dynamic conditions. To address this issue, we used an approach inspired by Olney and Winter (1985) during stepping-in-place. This task was used for studies on the control of body posture and locomotion (Breniere and Ribreau, 1998; Ivanenko et al., 2000) and presents spatio-temporal characteristics similar to gait (Garcia et al., 2001). From a mathematical point of view: (1) non-linear constrained optimization was implemented for the calculations and (2) the expressions were developed to account for the influence of the biarticularity of the muscles crossing the knee joint (Basmajian and De Luca, 1985, pp. 232–239). The results obtained from our approach are compared with those given by using other algorithms (Olney and Winter, 1985).

2. Methods

The proposed method is decomposed in two successive steps (Fig. 1): the first one is aimed to provide the best EMG processing in order to match the knee resultant joint moment under step isometric contractions determined using kinematic and kinetic data. An attempt was made to improve the performance of the model through EMG exponentiation since either linear, quasi-linear or quadratic relationships have been reported to exist between EMG and moment (Marras and Granata, 1997; Metral and Cassar, 1981). In the second step, the agonist and antagonist knee muscle moments are estimated with processed EMG signals (i.e., computed using the coefficients assessed from isometric calibration) and the resultant moment at the knee as input variables in dynamic conditions (stepping-in-place). The problem is formulated as a general optimization problem (Boggs and Tolle, 1996) with a criterion function that combined several components, as previously done by others (Seireg and Arvikar, 1973; Stokes and Gardner-Morse, 2001). Given the significance of muscle function and the possible distortions caused in the EMG, each muscle moment was balanced using a coefficient method inspired by Cholewicki and McGill (1994).

Nine healthy male volunteers (age, 23.2 ± 4.3 years; height, 1.80 ± 0.05 m; mass, 74.2 ± 6.1 kg, means $\pm$ SD) participated in this study. The anthropometric data used for calculations were taken from tables (Winter, 1990). EMG data were acquired using MYODATA®. Both kinematic and kinetic data were recorded with DATAC™. All data were synchronized by using a single electrical pulse acquired with DATAC™ and MYODATA® simultaneously. All computations were done using MATLAB (Math Works, Natick, MA).

2.1. Electromyography

For all procedures, surface EMG was recorded through bipolar electrodes (Meditrace, diameter 2 cm, Graphic Controls, Canada) with a 2 cm inter-electrode spacing. After appropriate skin preparation, the electrodes were positioned on the right leg, over the bellies of representative extensor and flexor muscles that function at the knee. Following the recommendations of Olney and Winter (1985) and Manal and Buchanan (2000), the biceps femoris (BF) and the gastrocnemius (GA) were chosen to adequately represent the muscular activity of the knee flexor group while the rectus femoris (RF) and the vastus medialis (VM) represent that of the knee extensor group. Under this hypothesis, the force production capacity of the selected muscles is assumed to be equivalent to that of their corresponding muscle group. The EMG signals were sampled at 1024 Hz, pre-