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Review

Methodological aspects of SEMG recordings for force estimation – A tutorial and review

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A B S T R A C T

Insight into the magnitude of muscle forces is important in biomechanics research, for example because muscle forces are the main determinants of joint loading. Unfortunately muscle forces cannot be calculated directly and can only be measured using invasive procedures. Therefore, estimates of muscle force based on surface EMG measurements are frequently used. This review discusses the problems associated with surface EMG in muscle force estimation and the solutions that novel methodological developments provide to this problem. First, some basic aspects of muscle activity and EMG are reviewed and related to EMG amplitude estimation. The main methodological issues in EMG amplitude estimation are precision and representativeness. Lack of precision arises directly from the stochastic nature of the EMG signal as the summation of a series of randomly occurring polyphasic motor unit potentials and the resulting random constructive and destructive (phase cancellation) superimpositions. Representativeness is an issue due the structural and functional heterogeneity of muscles. Novel methods, i.e. multi-channel monopolar EMG and high-pass filtering or whitening of conventional bipolar EMG allow substantially less variable estimates of the EMG amplitude and yield better estimates of muscle force by (1) reducing effects of phase cancellation, and (2) adequate representation of the heterogeneous activity of motor units within a muscle. With such methods, highly accurate predictions of force, even of the minute force fluctuations that occur during an isometric and isotonic contraction have been achieved. For dynamic contractions, EMG-based force estimates are confounded by the effects of muscle length and contraction velocity on force producing capacity. These contractions require EMG amplitude estimates to be combined with modeling of muscle contraction dynamics to achieve valid force predictions.

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1. Introduction

Surface EMG has found applications in many different fields, such as ergonomics (Hagg et al., 2000; Hoozemans and van Dieen, 2005), sports (Clarys and Cabri, 1993), clinical decision-making (Harlaar et al., 2000; Kleissen et al., 1998), prosthetics (Parker et al., 2006; Zecca et al., 2002), and biofeedback (Basmajian, 1988; Ince et al., 1985). EMG is useful because it is one of the few methods that provide a window on muscle activity and hence muscle force production during functional movements. Whereas inverse dynamics analysis allows calculation of the net output (moment) produced by all muscles spanning a joint, its use does not allow the calculation of force in individual muscles, given the mechanical indeterminacy of muscle-joint-systems (i.e. they have more muscles than kinematic degrees of freedom). Moreover, muscle force can be measured using invasive procedures only and only in some muscles (Finni et al., 1998; Dennerlein et al., 1998). Insight into the magnitude of muscle forces is important in biomechanics research, for example to understand motor control and because muscle forces are the main determinants of joint loading. Since EMG provides information on individual muscle activity, it can be of help here (Cholewicki and McGill, 1994; Hof and Van den Berg, 1981a; Lloyd and Besier, 2003; Staudenmann et al., 2007b), so that estimates of muscle force are frequently based on surface EMG measurements.

Muscle force is mainly determined by the number of active motor units (MUs), their size (cross-sectional area), and their firing rate (Milner-Brown and Stein, 1975). Therefore, in principle, both spatial (active MUs) and temporal (firing rates) information is required to estimate muscle force. The factors determining force are often summarized in the term *muscle activation*, which is not a physiological variable, but rather an abstract time-varying model input variable that scales the model output, muscle force. This input is conventionally estimated by means of single time-varying normalized EMG amplitude, which is affected by MU size, MU number and firing rates, but as a 1-dimensional signal can only provide an imperfect representation of all three factors. Recently, the added value of the spatial information provided by multi-channel EMG has been emphasized in several reports on EMG applications (Blok et al., 2002b; Drost et al., 2006; Farina et al., 2006; Garcia et al., 2005; Holtermann et al., 2005). It was also shown that this approach improves EMG-based force estimation (Staudenmann et al., 2005). Another pertinent problem is that the EMG amplitude is affected by factors not relevant to force production, such as the wave shape of motor unit action potentials (De Luca, 1997; Farina et al., 2004b). Also, with respect to this problem recent developments have suggested new solutions to improve muscle force estimation from EMG (e.g. Potvin and Brown, 2004).

The aim of this paper is to provide a tutorial and review current literature on methodological aspects that affect the relation between EMG and muscle force with an emphasis on the use of multi-channel surface EMG and signal processing methods as means to improve the validity of EMG-based muscle force estimation. Since specific populations, such as for example patients with neuromuscular diseases and elderly, may pose specific problems in EMG interpretation, we will limit ourselves to healthy, non-elderly adults. Validity of muscle force estimation is determined by several criteria, which will be discussed in this review. First, estimates of muscle activation should: (1) have a high precision (i.e. a high signal-to-noise ratio or low error variance), (2) be representative (i.e. reflect activity of the whole muscle under study) and (3) be selective (i.e. with minimal contributions of other signal sources). Note that these three criteria are also crucial in many EMG applications in which muscle force is not of primary interest. Subsequently, to attain valid force estimates from EMG amplitudes the following factors need to be considered: (1) the nature of the EMG–force relationship, (2) the differences in temporal characteristics between EMG and force signals, (3) the normalization of the EMG amplitude, and (4) the effects of muscle contraction dynamics.

It should also be noted that muscle force at a given level of muscle activity is affected by a range of factors not reflected in the EMG signal, such as instantaneous muscle length and rate of length change (Hof, 1997), contraction history (Welter and Bobbert, 2001) and fatigue (Lind and Petrofsky, 1979). Therefore, this review will focus mainly on isometric contractions of limited duration. During such contractions, the muscle–tendon complex remains at constant length and the EMG amplitude of muscles contributing to the net joint moment produced is closely related to the magnitude of the moment (Inman and Ralston, 1952; Lippold, 1952). Although, even in such contractions, changes in muscle fiber lengths can occur (Maganaris and Baltzopoulos, 1999), the effects on the force–EMG relation are often considered negligible. Force estimation will obviously also depend on the quality of the instrumentation and procedures used in signal acquisition, which are not addressed in the present review because they have been extensively discussed elsewhere (e.g. Clancy et al., 2002; Godin et al., 1991; Huigen et al., 2002; Metting van Rijn et al., 1990; Nishimura et al., 1992; Webster, 1984).

2. Basics of electromyography

This section describes biophysical fundamentals of EMG and highlights problems and limitations of using surface EMG in estimating muscle activity and muscle force.

2.1. Motor unit and motor unit potentials

The motor unit (MU) is the functional unit of the neuromuscular system (Liddell and Sherrington, 1925; Sherrington, 1925). MUs consist of an α-motoneuron and the connected muscle fibers and vary greatly in size (number and size of muscle fibers) (Buchthal et al., 1959; Feinstein et al., 1955). Contraction of a MU is initiated by an action potential traveling from the soma of the α-motoneuron, along its axon to reach its terminal branches, each of which connects to a muscle fiber at the so-called neuromuscular junction. Subsequently, depolarization of the muscle fiber membrane