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The concurrent validity of three computerized methods of muscle activity onset detection

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ABSTRACT

Although the visual (VIS) method for muscle activation onset detection has been the gold standard, this method has been criticized because of its moderate reproducibility and for being laborious. The simple threshold (STH), approximated generalized likelihood-step (AGL-step), and k-means (KM) algorithms are more repeatable and less laborious but require validation for gait speeds encountered in clinical research. We, therefore, assessed the intra-rater reliability of the VIS method and the concurrent validity of the algorithms against the VIS for 3 gait speeds. We recruited 10 healthy young adults (4 male, 6 female; mean age = 28.5 ± 4.2). Participants completed 10 walking trials each at 3 speeds. Electromyographic data from 1 gait cycle (GC) were collected from 6 right lower extremity muscles during each trial. We used custom Labview programs to determine muscle activity onset for all 4 methods. Repeatability coefficients for the VIS method ranged from 12.51% to 45.08% of the GC, depending on the muscle. The AGL-step algorithm agreed best with the VIS method (root mean squared error (RMSE) 0.86–6.95% of GC) followed by the STH (1.19–15.6% of GC) and KM (4.6–16.9% of GC) methods. A single rater demonstrated large errors (RMSE 8–23% of GC) between VIS assessments. Based on this study's parameters, the AGL-step agreed best with the VIS method and may be an alternative to the VIS.

1. Introduction

The accurate detection of muscle activity onset from electromyographic (EMG) signals is a requirement in motor control, biomechanical and clinical research studies. Visual muscle onset determination (VIS) by an experienced examiner is considered the gold standard because the examiner is able to evaluate all the details of the signal when determining muscle activity onset (Walter, 1984). However, the method has been criticized (Hodges and Bui, 1996; Staude and Wolf, 1999) because the reproducibility and repeatability (inter- and intra-tester) were only moderate (ICC = 0.46–0.60; repeatability: 51%) (Di Fabio, 1987). Additionally, the VIS method of onset determination becomes prohibitive with large numbers of trials due to the substantial amount of time required for processing.

Computer programs using algorithms, such as the simple threshold (STH) (Di Fabio, 1987; Hodges and Bui, 1996), the approximated generalized likelihood-step (AGL-step) (Roetenberg et al., 2003; Staude et al., 2001; Staude and Wolf, 1999; Staude, 2001), and k-means (KM) methods (Den Otter et al., 2006), overcome the limitations of the gold-standard VIS method by being 100% repeatable (Di Fabio, 1987) and less labor intensive (Drapała et al., 2012). The STH method is the most commonly used algorithmic method, possibly because of its simplicity. For this method, the muscle is determined to be active when the amplitude of the signal rises above some predetermined threshold when compared to the baseline signal. For example, researchers have used 2, 3, or 10 standard deviations over the mean baseline signal as the threshold (Chambers and Cham, 2007; Di Fabio, 1987; Lynch et al., 1996). However, because the relative strength of the signal to noise ratio (SNR) in EMG recordings vary between trials and subjects, the heuristically chosen threshold has been shown to introduce errors into onset determination (Di Fabio, 1987; Staude et al., 2001; Staude and Wolf, 1999; Staude, 2001).

The AGL-step and KM algorithms may improve upon both the VIS and STH methods. The AGL-step includes a post-processor

Abbreviations: VIS, visual onset determination; AGL-step, approximated generalized likelihood-step; KM, k-means; EMG, electromyographic; SNR, signal-to-noise ratio; SS, self-selected; SL, slow; VS, very slow; RF, rectus femoris; VM, vastus medialis; BF, biceps femoris; ST, semitendinosus; TA, tibialis anterior; MG, medial gastrocnemius; GC, gait cycle; RMSE, root mean squared error.

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based on a maximum likelihood function that aims to improve upon onset time detection, while the KM eliminates the need to set an operator dependent threshold altogether. These factors may make these algorithms more suited to clinical gait studies where, due to the varying nature of disability, participants walk at a range of speeds. Under these conditions the SNR varies in a natural manner determined by the strength of the contraction (Den Otter et al., 2004; Hof et al., 2002). The ability of these algorithms to accurately detect onset of muscle activity over a range of gait speeds is therefore important.

In a study comparing the STH and AGL-step methods, Solnik et al. demonstrated that the AGL-step method agreed better with the VIS method than the STH method, based on EMG data collected from subjects walking at relatively fast speeds (1.2–1.8 m/s) (Solnik et al., 2010). Previous studies have also evaluated a class of algorithms that like the KM method do not require setting a threshold a priori (Drapała et al., 2012; Vannozzi et al., 2010). These algorithms, like the KM method, are potentially beneficial because they avoid the initial processes of establishing a user dependent threshold (Vannozzi et al., 2010). Evidence, from non-gait data, suggests that these "K-mean like" algorithms may be better than the AGL method (Drapała et al., 2012). However, because the different classes of algorithms have not been validated together against the VIS method across the range of gait speeds encountered in clinical research, it is unknown which algorithm operates best at this range of speeds.

Therefore, the purpose of this investigation was twofold: (1) to assess the intra-rater reliability of the VIS method; and (2) to assess the concurrent validity of the STH, AGL-step, and KM algorithmic methods against the VIS method, during over-ground gait, at 3 speeds.

2. Methods

2.1. Subjects

Ten subjects (4 male, 6 female; mean age = 28.5 ± 4.2 years) were recruited and provided informed consent prior to testing. A screening form was completed to ensure all subjects had no history of neuromuscular or cardiovascular diseases, surgery to the lower limbs within the past year, musculoskeletal injury within the past 6 months, consumed drugs or alcohol within 24 h or caffeine within 8 hours prior to testing. A university institutional review board approved all procedures.

2.2. Instrumentation

EMG data were collected using an 8 channel amplifier (Bagnoli 8, Delsys Inc., Boston, MA) and bipolar surface electrodes (Ag/AgCl, 10 mm $\times$ 1 mm bars with an inter electrode distance of 10 mm, DE 2.1, Delsys Inc. Boston, MA, USA). Data were collected from 6 right lower extremity muscles: rectus femoris (RF), vastus medialis (VM), biceps femoris (BF), semitendinosus (ST), tibialis anterior (TA), and medial gastrocnemius (MG). The skin over each muscle was lightly abraded and the electrodes placed in accordance with the SENIAM protocol (Hermens et al., 2000). The EMG signals were amplified ($\times$1000), band pass filtered (20–450 Hz), and sampled at 1320 Hz.

The gait events (heel-strikes and toe-offs) for each single stride were defined using 2 force plates sampling at 1320 Hz (Kistler Inc., Amherst, NY) and kinematic data, collected using 5 Oqus cameras sampling at 120 Hz (Qualisys Inc., Gothenburg, Sweden). Specifically, once the vertical ground reaction force rose above or fell below 0.1 N and remained for 5 frames, heel-strike and toe-off were defined, respectively. In addition, to define the entire gait cycle, kinematic data was used to identify events that occurred with the foot off the force plates. Specifically, the initial minimum position of the heel marker and the first initial rise from the minimum position of the toe marker were used to define heel-strike and toe-off respectively. The force plate and motion capture data were collected together and synchronized with the EMG data. Infrared light gates (FarmTek, Wylie, TX) were used to monitor and control gait speed during all trials. All data were exported to Visual 3D (C-motion Inc., Bethesda, MD) where gait events were identified from force plate and motion capture data by an automated program and verified by visual inspection before being used to separate the EMG signal into a single gait cycle (GC). Each walking trial yielded only 1 GC. The EMG signal was then rectified and normalized to 1000 points (representing 100% of GC, in 0.1% increments) and each muscle's activity onset during all trials was determined via 4 distinct methods (VIS, STH, KM, AGL-step), using custom written software (Labview 8.6, National Instruments, Austin, TX).

2.3. Procedures

Each participant completed 30 walking trials, 10 at each of 3 speeds while one GC cycle was collected per walking trial. All subjects first walked at self-selected (SS; ±10%) then slow (SL; 60% self-selected ± 10%) and very slow (VS; 30% self-selected ± 10%) speeds on a 7 m level-ground walkway. Prior to data recording, participants were allowed to practice walking at each speed until they were able to consistently maintain the requisite speed.

2.4. Data analysis

Two analyses were performed: (1) Intra-rater reliability of the VIS method; and (2) Concurrent validity of the algorithmic methods against the VIS method. Data from all trials across all speeds were combined in the analyses. All data were visually inspected and custom LabView software was used to perform all analyses. For the reliability of the VIS method, all 300 trials were analyzed on 2 separate occasions (at least 3 days apart), by the same rater, and the values compared for consistency. For the concurrent validity of the algorithmic methods, only a subset of the trials was used for comparison. Of the 300 trials used to determine the reliability of the VIS method, only those with a difference between onset determinations of 0.8% of the GC or less, for the 2 visual assessments by the same rater, were used to compare to the 3 algorithmic methods. The choice of 0.8% was the consequence of the fact that the width of the cursor, for the VIS method, was 0.4% of the GC. Therefore, an error of 0.8% or less between readings was determined to be associated with measurement error and not accuracy in onset determination. Thus, depending on the muscle, between 77% (RF) and 97% (TA) of trials were used in the final analysis. Multiple combinations of parameters were evaluated for 60 trials collected from 2 participants to determine the optimal parameters needed to accurately determine EMG onset (determined by the VIS method), across the 6 muscles evaluated, for the STH, AGL-step, and KM algorithms. EMG onset determination for each of the 4 methods is described below.

2.4.1. VIS method

To determine EMG onset using the VIS method, the EMG data were first rectified, but not enveloped/smoothed. Then, one examiner determined EMG muscle activity onset from the rectified signals by identifying a rise in the EMG signal beyond the baseline level that remained above baseline for 3% of the GC. Baseline EMG activity was defined as the lowest mean 10% of the GC using a sliding window process. A cursor was placed over the point where onset was determined to have occurred. The onset time