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Use of muscle synergies and wavelet transforms to identify fatigue during squatting

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ABSTRACT

The objective of this study was to supplement continuous wavelet transforms with muscle synergies in a fatigue analysis to better describe the combination of decreased firing frequency and altered activation profiles during dynamic muscle contractions. Nine healthy young individuals completed the dynamic tasks before and after they squatted with a standard Olympic bar until complete exhaustion. Electromyography (EMG) profiles were analyzed with a novel concatenated non-negative matrix factorization method that decomposed EMG signals into muscle synergies. Muscle synergy analysis provides the activation pattern of the muscles while continuous wavelet transforms output the temporal frequency content of the EMG signals. Synergy analysis revealed subtle changes in two-legged squatting after fatigue while differences in one-legged squatting were more pronounced and included the shift from a general co-activation of muscles in the pre-fatigue state to a knee extensor dominant weighting post-fatigue. Continuous wavelet transforms showed major frequency content decreases in two-legged squatting after fatigue while very few frequency changes occurred in one-legged squatting. It was observed that the combination of methods is an effective way of describing muscle fatigue and that muscle activation patterns play a very important role in maintaining the overall joint kinetics after fatigue.

1. Introduction

Humans have the ability to perform dynamic movements with little to no conscious effort; however due to the high dimensionality of the neuromuscular system, the underlying mechanisms to perform such tasks are highly complex. Electromyography (EMG) is a commonly used tool for recording and analyzing the role of skeletal muscle during movement. Due to the large number of muscles used in various tasks, it can be difficult to decipher individual muscle activations and their contributions in the larger context of movements such as squatting. This drawback has been recently addressed using non-negative matrix factorization (NNMF) to perform muscle synergy analyses, decomposing large quantities of EMG data into a few, simpler components that can be used to describe muscle roles in a certain task (Tresch et al., 2006).

An increasing amount of studies have used muscle synergies to describe human gait and it has been seen that level walking can be described by four (Barroso et al., 2014), five (Ivanenko et al., 2004) or six (Allen and Neptune, 2012) synergies. In addition to human gait, muscle synergies have also been used to analyze natural motor behaviours in frogs such as kicking (d'Avella et al., 2003), jumping, swimming and walking (d'Avella and Bizzi, 2005). Here it was observed that three shared, plus a varying number of task-specific synergies, were necessary to decompose the EMG signals of each task indicating that the central nervous system (CNS) may build off of a general template, adding activations for fine-tuning as necessary for specific tasks.

With respect to human exercises, Kristiansen et al. (2015) examined muscle synergies used in bench pressing for trained and untrained individuals. They observed that two synergies were sufficient in describing the movement and that more than 95% of the variance was accounted for (VAF). These two synergies corresponded to movement phases as one characterized the concentric phase, while the other represented the eccentric phase. Synergies have also been used to analyze fatigue during a cyclic, rowing task (Turpin et al., 2011). They observed that three synergies achieved more than 90% VAF in EMG profiles before and after the participants rowed until exhaustion. The authors noted only minor changes in synergy activations, which led the authors to postulate

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that fatigue-induced differences are predominantly seen in muscle firing frequencies rather than changes in the organization of muscle coordination. Unfortunately, these authors neglected to include a frequency analysis and thus, their conclusions are unsupported.

Spectral changes to the EMG signal due to fatigue can be attributed to firing frequency but can also be caused by other central mechanisms such as motor unit synchronization (Hermens et al., 1992) and peripheral mechanisms such as a change in motor neuron conduction velocity (Arendt-Nielsen and Mills, 1985) or a variety of other intramuscular responses (Kirkendall, 1990). Traditional amplitude and frequency analyses have been used to effectively detect these central and peripheral changes to evaluate fatigue in isometric conditions (Viitasalo and Komi, 1977). These methods cannot be effectively applied to dynamic conditions, however, as (1) the EMG signal is not stationary, and (2) there is a relative shift of the electrodes in relation to the origin of action potentials, and the conductivity properties of the soft tissue separating the electrodes from the muscle fibres (Farina, 2006). These limitations of using surface EMG in dynamic contractions can be addressed by conducting short-time Fourier transforms (STFT) in short time epochs to account for the non-stationarity. When using an STFT, the dynamic signal is windowed to small enough periods of time where the contraction can be assumed to be stationary as the traditional Fourier transform has no resolution in the time domain. In certain dynamic tasks with large joint ranges of motions such as squatting, muscle fibres undergo considerable movement in relation to the surface electrodes. Therefore, windowing may not be the most effective technique in analyzing the non-stationary signal as the epoch would have to be quite small in order to negate muscle fibre movement and assume stationarity. Since continuous wavelet transforms (CWT) scale and translate a mother wavelet, they are not limited to the assumption of stationarity and thus, are an attractive alternative. They have been effectively applied to dynamic contractions (Karlsson et al., 2001; Hostens et al., 2004; Cifrek et al., 2009) and have shown better accuracy and precision than other time–frequency methods including STFT (Karlsson et al., 2000).

Even though traditional amplitude and frequency analyses have been effective in quantifying the fatigue-related increases in activation amplitude and decreases in firing frequency during isometric tasks (Viitasalo and Komi, 1977), these techniques are, as noted above, not suitable for dynamic movements (Farina, 2006). Therefore, the primary aim of this study is to supplement CWT with muscle synergy extraction in a fatigue analysis to better describe the combination of decreased firing frequency and altered activation profiles during dynamic muscle contractions. It is hypothesized that similar to isometric contractions, fatigue-related changes during dynamic contractions will be in the form of decreases in muscle firing frequency and altered muscle activation patterns, which will be effectively elucidated through the combined use of CWT and muscle synergies.

2. Methods

2.1. Participants

Nine healthy young adults (23.7 ± 1.6 years; 5 male) participated in this study. Exclusion criteria were previous reports of significant lower limb injuries within six months of participation, or any other physical impairment that may influence knee function. All participants read and signed an informed consent form prior to data collection. The study was approved by the university's ethics review board.

2.2. Electromyography

Skin preparation included shaving and wiping the muscle belly down with an alcohol swab. Twelve bipolar surface EMG electrodes (electrode dimensions: 10.0 × 1.0 mm; inter-electrode distance: 10 mm; SP-E04, DE 2.1 DelSys Inc., USA) connected to a 16-channel EMG system (DS-B04, Bagnoli-16, DelSys Inc., USA) were placed over the muscle bellies of the gluteus maximus (GLTMAX), gluteus medius (GLTMED), tensor fascia lattae (TFL), rectus femoris (RFEM), vastus medius (VMED), vastus lateralis (VLAT), long head of biceps femoris (BFEM), semitendinosus (STEN), tibialis anterior (TA), medial gastrocnemius (MGAS), lateral gastrocnemius (LGAS), and the soleus (SOL). EMG was recorded from the dominant limb, which was determined by which leg would be used to kick a soccer ball a maximal distance. Electrode placements followed the guidelines outlined by SENIAM (Hermens et al., 2000).

MVIC data were collected using an isokinetic dynamometer (850-000, Biodex, USA). Plantar and dorsiflexion maximal efforts were collected with the ankle at 100°, knee flexion and extension maximal efforts were collected with the knee at 45° and hip flexion, extension and adduction were collected with the participant standing with a straight leg. Three MVICs for each seven second ramped contraction were completed with a 45 s rest period between each exertion. In an effort to optimize the myoelectric signal power to low frequency noise ratio for our application (Stegeman and Hermens, 1998; van Boxtel, 2001; Clancy et al., 2002; De Luca et al., 2010), all EMG signals were sampled at 1000 Hz, amplified by a gain of 1000, and band-pass filtered at 20–450 Hz.

2.3. Movement trials and fatigue protocol

Motion data were collected using a 15-camera infrared motion capture system (MX-40 cameras; Vicon Nexus, v1.7, UK) at 200 Hz with a Helen Hayes full-body marker set. Three dimensional ground reaction forces were collected using two force platforms (FP4060-08, Bertec, USA).

Participants first completed three successful one-legged squats on the dominant limb. During the one-legged squats, participants were only asked to squat at their own pace, keep their non-dominant leg behind and squat down as low as possible.

To fatigue the participants, a bench was adjusted to the participant's tibia height and the participant began two-legged squatting at a metronome-controlled pace of 35 squats per minute while holding a standard 20.4 kg Olympic bar on their shoulders. Participants continued to squat until complete exhaustion, which corresponded to a maximal value on the Borg Scale of Perceived Exertion (Borg, 1982). The average time to exhaustion was 8.2 ± 3.9 min. Three of the first five recorded squats were used for the non-fatigued state, while three of the last five were used for fatigued state. Once exhausted, participants completed three more successful one-legged squats with all collections occurring within minutes of the fatigue to avoid recovery as much as possible. The selection of successful squats was based on proper balance and form, foot contact occurring completely on the force plates and markers being recognized by the motion capture system.

2.4. Data analysis

Trajectories and ground reaction forces were analyzed in Visual 3D (v.4, C-Motion, USA) and were smoothed with a 4th order zero-lag low-pass Butterworth filter with a 10 Hz cut-off. Lower limb joint sagittal plane kinetics and kinematics were computed in Visual 3D with the Helen Hayes model (Kadaba et al., 1990). EMG signals were analyzed in Matlab (2014a, MathWorks, USA) and processed with a 4th order zero-lag high-pass Butterworth