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Muscle synergies during bench press are reliable across days

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ABSTRACT

Muscle synergies have been investigated during different types of human movement using nonnegative matrix factorization. However, there are not any reports available on the reliability of the method. To evaluate between-day reliability, 21 subjects performed bench press, in two test sessions separated by approximately 7 days. The movement consisted of 3 sets of 8 repetitions at 60% of the three repetition maximum in bench press. Muscle synergies were extracted from electromyography data of 13 muscles, using nonnegative matrix factorization. To evaluate between-day reliability, we performed a cross-correlation analysis and a cross-validation analysis, in which the synergy components extracted in the first test session were recomputed, using the fixed synergy components from the second test session. Two muscle synergies accounted for >90% of the total variance, and reflected the concentric and eccentric phase, respectively. The cross-correlation values were strong to very strong (r-values between 0.58 and 0.89), while the cross-validation values ranged from substantial to almost perfect (ICC3, 1 values between 0.70 and 0.95). The present findings revealed that the same general structure of the muscle synergies was present across days and the extraction of muscle synergies is thus deemed reliable.

1. Introduction

For successful execution of movement, both timing and pattern of activation of all involved muscles need to be well coordinated. However, at the moment there are unknown aspects of how the central nervous system controls the muscles involved in movements. One theory on how the central nervous system controls human movement, infers that movements to a large extent are controlled by a combination of a few basic activation patterns, also known as motor modules or muscle synergies (Bernstein, 1967; Ivanenko et al., 2006; Lacquaniti et al., 2012). A muscle synergy can be characterized as a low dimensional organizational structure controlling multiple muscles. These neural coordinative structures are thought to be located at spinal level, and to be controlled by motor cortical areas and affected by afferent systems (Bizzi and Cheung, 2013). Muscle synergies have thus been suggested to provide a simplified strategy for the nervous system to control movements (Bernstein, 1967; D'Avella and Bizzi, 2005; Hug, 2010; Ivanenko et al., 2006; Torres-Oviedo et al., 2006; Torres-Oviedo and Ting, 2007). Indeed, a few basic patterns have been shown to adequately describe a number of various movements in humans such as reaching in the horizontal plane (Muceli et al., 2010, 2014) standing (Krishnamoorthy et al., 2003; Torres-Oviedo and Ting, 2007), walking (Ivanenko et al., 2004; MacLellan et al., 2014; Oliveira et al., 2014), running (Cappellini et al., 2006), pedaling (Dorel et al., 2009; Hug et al., 2010, 2011), rowing (Turpin et al., 2011a, 2011b), bench press (Kristiansen et al., 2015b), and backward giant swing (Frère and Hug, 2012).

To study inter-muscular coordination during movements, muscle synergies can be extracted from multiple surface electromyography (EMG) signals using a nonnegative matrix factorization algorithm. The extraction of muscle synergies offers unique insight into the combined timing and activation patterns of multiple muscles during movements. Muscle synergies are reported to be consistent across a variety of postural perturbations in cats (Torres-Oviedo et al., 2006) and to be robust in human balance control across different biomechanical contexts in humans (Torres-Oviedo and Ting, 2010). Consistency has also been reported for pedaling (Hug et al., 2011).

However, there are to the best of the authors' knowledge not any reports available on within- and between-day reliability of the method. Thus, the aim of the study was to evaluate the between-day reliability of applying nonnegative matrix factorization to EMG data collected during bench press. Considering the consistency and robustness of muscle synergies, we hypothesized

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that muscle synergies describing bench press would be reliable across days. Investigations reporting both the absolute and relative reliability are needed to provide evidence that muscle synergy analyses based on nonnegative matrix factorization are clinically and experimentally sound. The presentation of this reliability study follows the guidelines for reporting reliability and agreement studies (Kottner et al., 2011).

2. Materials and methods

2.1. Participants

Healthy male individuals (n = 21, age 24.5 ± 2.2 years (mean ± standard deviation (SD)), height 1.81 ± 0.07 m, body mass at first and second test session 88.5 ± 13.1 kg and 89.0 ± 12.8 kg, three repetition maximum (3RM) in bench press at first and second test session 109.2 ± 26.1 kg and 109.4 ± 25.9 kg) volunteered for participation in the current study. At the time of data collection, all participants had performed full body strength training for 2–3 times per week for at least two years. The number of participants was determined using an α level set to 0.05, β level to 0.20, p_0 to 0.7, p_1 to 0.9, and n to 2 (Walter et al., 1998). p_0 and p_1 denotes the minimally acceptable level of reliability and the expected level of reliability, respectively. α level and β level denotes the probability of making a type 1 and type 2 error, respectively. All participants gave their written informed consent after having been explained the experimental methods and risks. The study was approved by the local ethics committee of North Denmark Region (N-20120036).

2.2. Experimental procedure

As a means to study the reliability of extracting muscle synergies during a strength training movement, we applied the common exercise of bench press. For trained individuals, bench press is a demanding and complex bilateral arm movement. Proper execution requires the coordinated activation of all major muscle groups in the legs, back and upper body, while handling a heavy load. The study consisted of three sessions. The purpose of the first session was to familiarize the participants with the test protocol, laboratory environment and test equipment, as well as to minimize learning effects in the two subsequent sessions. Approximately one week after the familiarization session, all participants performed two test sessions for investigation of between-day reliability of muscle synergies during bench press. The time interval between the first and the second test session was on average 8.2 ± 2.9 days. In the test sessions, the participants performed the following: warm up, a 3RM test in bench press, one set of 3 repetitions at 75% of the 3RM load for normalization, and then three sets of eight repetitions at 60% of the 3RM load for investigation of reliability. It was necessary to apply a submaximal intensity level during the bench press that was used for investigation of reliability as a minimum of 20–40 cycles are required during cyclic tasks to obtain representative EMG data (Hug, 2010; Oliveira et al., 2014). As there are no conclusive recommendations on how to normalize EMG data, we used a task-specific submaximal dynamic normalization procedure, which we have previously used in a similar experimental setup (Kristiansen et al., 2015b). Briefly, the task-specific submaximal dynamic normalization procedure consisted of recording the maximal surface EMG envelope on the below mentioned muscles during the execution of a submaximal bench press at 75% of 3RM. The obtained value in this procedure was then used as a normalization factor.

2.3. Test sessions

First, the involved skin areas were shaved and cleaned with alcohol. Then, surface EMG electrodes (Ambu Neuroline 720 01-K/12, Ag/AgCl, inter electrode distance 20 mm, Ambu A/S, Ballerup, Denmark) were placed on the skin over the following muscles on the right side of the body: pectoralis major (PM), anterior deltoideus (AD), biceps brachii (BB), triceps brachii, lateral head (TBL), triceps brachii, medial head (TBM), latissimus dorsi (LD), erector spinae (ES), rectus femoris (RF), biceps femoris (BF), gastrocnemius lateral head (GML), soleus (SOL), vastus lateralis (VL), and vastus medialis (VM). The electrodes were mounted along the muscle fiber direction in a bipolar configuration. Most of the electrodes were mounted according to the SENIAM recommendations (Hermens et al., 2000). For PM and LD, which are not listed by SENIAM, the electrodes were mounted four fingerbreadths below the clavicle, medial to the anterior axillary border and 3 fingerbreadths distal to and along the posterior axillary fold, parallel to the lateral border of scapula (Lehman et al., 2006), respectively. All electrodes were mounted by the same researcher in both test sessions. A reference electrode was mounted on the ankle, at the lateral malleolus.

After the placement of the electrodes, participants performed a progressive warm up regimen by lifting increasingly heavier loads in bench press. Bench press was performed using an ER-Equipment power rack (ER Equipment, Albertslund, Denmark). For the 3RM test, the load was increased by 2.5–10 kg per set of 3 repetitions, until 3RM was found. On average 4 sets were required for the determination of the 3RM. Four min rest was applied between all sets.

After successful completion of the 3RM test, the load was decreased to 75% of the 3RM load and 3 repetitions were performed. Participants were instructed to perform the eccentric phase in approx. 1 s and the concentric phase as fast as possible for the 3RM test and the normalization set. The EMG data obtained during these repetitions was used for normalization purpose.

Finally, the load was further decreased to 60% of the 3RM load, and the last 3 sets of 8 repetitions were completed. This resulted in a total of 24 repetitions with a cyclic pattern consisting of approx. 1 s eccentric phase and 1 s concentric phase. The data recorded during these repetitions were used to study the between–day reliability of muscle coordination. A potentiometer (model KS60, NTT Nordic Transducer, Hadsund, Denmark) was connected to the middle of the barbell for measurement of the vertical position. A bench press cycle was defined as the period between two successive top positions. To avoid any initial transition, the first bench press cycle of each set was removed from the data resulting in the concatenation of 21 cycles per participant. In the second test session, the exact same procedure was applied.

2.4. Data recording and processing

The surface EMG signals were recorded using a 128-channel surface EMG amplifier (EMG-USB, LISiN - OT Bioelectronica, Turin, Italy) where they were amplified using an individual-specific gain factor (100–500) and band-pass filtered [10–750 Hz] before being sampled at 2048 Hz. Furthermore, a notch filter (4th order Butterworth band stop with rejection width of 1 Hz centered at the first three harmonics of the power line frequency of 50 Hz) was used to remove line interference. The linear envelopes of the EMG measurements across each of the bench press cycles were obtained by low pass filtering (zero-lag Butterworth, 2nd order, 4 Hz) of the rectified EMG. Each of the EMG envelopes was then interpolated into 100 time points. During the normalization set performed at 75% of 3RM, the first and last half second of the EMG measurements were excluded. The linear envelopes of the EMG measure-