Journal of Electromyography and Kinesiology 30 (2016) 209–215

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

# Influence of locomotion speed on biomechanical subtask and muscle synergy

Kai Gui, Dingguo Zhang *

State Key Laboratory of Mechanical System and Vibration, Institute of Robotics, School of Mechanical Engineering at Shanghai Jiao Tong University, China

ARTICLE INFO

*Article history:*
Received 1 June 2016
Received in revised form 28 June 2016
Accepted 30 July 2016

*Keywords:*
Locomotion
Muscle synergy
Walking speed
Biomechanical subtask
Electromyography

ABSTRACT

This paper investigates the relationship of biomechanical subtasks, and muscle synergies with various locomotion speeds. Ground reaction force (GRF) of eight healthy subjects is measured synchronously by force plates of treadmill at five different speeds ranging from 0.5 m/s to 1.5 m/s. Four basic biomechanical subtasks, body support, propulsion, swing, and heel strike preparation, are identified according to GRF. Meanwhile, electromyography (EMG) data, used to extract muscle synergies, are collected from lower limb muscles. EMG signals are segmented periodically based on GRF with the heel strike as the split points. Variability accounted for (VAF) is applied to determine the number of muscle synergies. We find that four muscle synergies can be extracted in all five situations by non-negative matrix factorization (NMF). Furthermore, the four muscle synergies and biomechanical subtasks keep invariant as the walking speed changes.



## 1. Introduction

Locomotion is a common daily activity that is complex and requires redundant, cyclic movements. To achieve stable and natural gait, all muscles and joints of legs need to be engaged and coordinated. The aim of our study is to examine the relationship among walking speed, biomechanical subtasks of locomotion, and muscle activation patterns.

Typical gait cycles include a sequence of three sub-phases in stance (heel strike, flat foot contact, push off), and a sub-phase in swing (limb swing) (Agostini et al., 2014). A successful gait cycle includes corresponding biomechanical subtasks: heel strike, body support, forward propulsion, and leg swing (Zajac et al., 2003; Neptune et al., 2004).

To perform these subtasks successfully and sequentially, complicated muscle activation patterns are needed. Many studies have indicated that these patterns may be performed through motor modules or muscle synergies (d'Avella et al., 2003; Ivanenko et al., 2005; Cappellini et al., 2006; Bernstein, 1967; De Marchis et al., 2013; Routson et al., 2013; Gizzi et al., 2012). For human locomotion, studies have shown that four or five muscle synergies are sufficient to describe most muscle activation patterns (Cappellini et al., 2006; Clark et al., 2010). Clark et al. showed that the complexity and variability of muscle activity could be accounted for by a small set of muscle synergies over a wide range of normal speeds in healthy adults through non-negative matrix factorization (NMF) Clark et al., 2010. Ivanenko et al. successfully decomposed the EMGs matrix to basic temporal components and weighting coefficients through factor analysis (Cappellini et al., 2006; Ivanenko et al., 2004, 2006). They found that five basic activation patterns (temporal components) were enough to account for muscle activity during human locomotion (Ivanenko et al., 2004). Furthermore, these basic activation patterns held stable and consistent across a wide range of normal speeds.

However, the previous studies did not investigate the muscle synergies and biomechanical tasks simultaneously, among different locomotion speeds by experiments. This work aims to explore the muscle synergies and biomechanical tasks at various walking speeds based on experiments targeting walking on a treadmill with force plates.

## 2. Methods

### 2.1. Experimental protocol

Eight subjects (S1–S8) participated in this experiment (age: 22.4 ± 4 years (mean ± sd), height: 168 ± 11 cm, weight: 60 ± 18 kg). The experiment was approved by the Ethics Committee of Shanghai Jiao Tong University, China.

Subjects were required to walk on an instrumented split-belt treadmill (Bertec, USA) at five different speeds: 0.5 m/s, 0.75 m/s,

* Corresponding author.
*E-mail address:* dgzhang@sjtu.edu.cn (D. Zhang).

http://dx.doi.org/10.1016/j.jelekin.2016.07.010
1050-6411/

1.0 m/s, 1.25 m/s, and 1.5 ± 0.01 m/s (see Fig. 1). Before the experiment, subjects were familiarized with the treadmill by walking at the five speeds. This treadmill has force plates in two tracks, and can simultaneously sample contact pressure (also named as ground reaction force, GRF) on the two tracks at 800 Hz. Subjects kept their legs separately on the two tracks. The GRF of two tracks would be measured separately. The GRF was used to identify the biomechanical subtasks during locomotion.

EMG signals from eight targeted muscles of right leg were collected during walking at 2000 Hz at a bandwidth of 20–450 Hz by a commercial EMG system (Trigno TM Wireless system, Delsys Inc.). The eight muscles are gluteus medius (Gmed), rectus femoris (RF), vastus lateralis (VL), biceps femoris (BF), semitendinosus (ST), gastrocnemius medius (GM), soleus (SO), and tibialis anterior (TA) (see Fig. 1). Before EMG data acquisition, the targeted skin areas were cleaned with alcohol to reduce contact impedance. Muscle synergies were acquired from EMG matrices by NMF at different locomotion speeds.

The whole experiment contained five trials. Each trial lasted two minutes with one specific walking speed. Two-minute rest intervals were included to avoid fatigue and adaptation between each two adjacent trials. GRF of the two legs and EMG signals of eight muscles were recorded during every trial synchronously.

### 2.2. Data processing

Raw GRF signals were low-pass filtered by a zero-lag 2nd-order Butterworth digital filter with a cutoff frequency of 5 Hz. Based on the GRF, heel strike, flat foot contact, and swing phases were determined. Raw EMG signals were rectified and low-pass filtered at 5 Hz with a zero-lag 2nd-order Butterworth digital filter (Barroso et al., 2014).

After synchronizing the GRF data and EMG data, EMG signals were segmented into cycle-by-cycle sequences, with heel strike as the starting point. A gait cycle was defined as the duration between two consecutive right heel strikes. The EMG profiles of 20 continuous cycles were averaged to obtain the final EMG profile for a gait cycle (Ivanenko et al., 2004). Every EMG profile was normalized and time-interpolated to fit a normalized 100-point data base (Ivanenko et al., 2004).

### 2.3. Non-negative matrix factorization

The NMF algorithm is a multivariate statistical data analysis technique, based on Lee and Seung (1999). The basic formula for the NMF is to approximate the original EMG matrix $E$ ($m \times t$ matrix, where m indicates the number of muscles and t represents the time base) with a linear combination of n ($n < m$) basic temporal components:

$$E = WH + residual \tag{1}$$

where H denotes the basic activation timing profile ($n \times t$ matrix) and W is independent with time ($m \times n$ matrix), which are muscle synergies.

A key step is to determine the number of muscle synergies extracted from the EMGs matrix. A common method to accomplish this is to measure the variability (Eq. (2)) of reconstructed EMG ($EMG_r$) by muscle synergies accounted for raw EMG ($EMG_o$) (Clark et al., 2010; Ivanenko et al., 2004; Tresch et al., 2006; d'Avella et al., 2006). The minimum number, whose variability accounted for (VAF) exceeds a preset threshold (here is 90%), is regarded as the number of muscle synergies. This critical threshold is mainly chosen empirically.

**Fig. 1.** The experimental setups. Eight EMG sensors are attached on the positions over target muscles of the legs.