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FAST CHANGES IN DIRECTION DURING HUMAN LOCOMOTION ARE EXECUTED BY IMPULSIVE ACTIVATION OF MOTOR MODULES

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Abstract—This study investigated the modular control of complex locomotor tasks that require fast changes in direction, i.e., cutting manoeuvres. It was hypothesized that such tasks are accomplished by an impulsive (burst-like) activation of a few motor modules, as observed during walking and running. It was further hypothesized that the performance in cutting manoeuvres would be associated to the relative timing of the activation impulses. Twenty-two healthy men performed 90° side-step cutting manoeuvres while electromyography (EMG) activity from 16 muscles of the supporting limb and trunk, kinematics, and ground reaction forces were recorded. Motor modules and their respective temporal activations were extracted from the EMG signals by non-negative matrix factorization. The kinematic analysis provided the velocity of the centre of mass and the external work absorbed during the load acceptance (negative work, external work during absorption (W-Abs)) and propulsion phases (positive work, external work during propulsion (W-Prp)) of the cutting manoeuvres. Five motor modules explained the EMG activity of all muscles and were driven in an impulsive way, with timing related to the initial contact (M2), load acceptance (M3), and propulsion (M4). The variability in timing between impulses across subjects was greater for cutting manoeuvres than for running. The timing difference between M2 and M3 in the cutting manoeuvres was significantly associated to W-Abs (r^2 = 0.45) whereas the timing between M3 and M4 was associated to W-Prp (r^2 = 0.43). These results suggest that complex locomotor tasks can be achieved by impulsive activation of muscle groups, and that performance is associated to the specific timing of the activation impulses.

Key words: side-step cutting, motor modules, EMG, motor performance.

INTRODUCTION

It has been suggested that the many mechanical degrees of freedom to be controlled during locomotion are modulated by the CNS at a low-dimensional level, by activating sets of relative intensities or weightings (motor modules) of muscle activation that are recruited in a specific sequence. Such motor modules are believed to represent neural structures in the spinal cord, activated by descending neurons and central pattern generators, combined to afferent input to produce a wide range of movements (d'Avella et al., 2003; Ivanenko et al., 2005; Muceli et al., 2010; Lacquaniti et al., 2012b). A consistent observation in human locomotion is that four to six motor modules are activated by sequential impulses of activity that provide the timing for synchronous activation of muscles over time (Ivanenko et al., 2004, 2006; Cappellini et al., 2006; Gizzi et al., 2011; Lacquaniti et al., 2012b). The specific timing of activity of motor modules allows for a precise association to gait events, such as the initial contact, load acceptance, and push off (Ivanenko et al., 2008).

Although the muscle weightings are flexible and may change across tasks (Lacquaniti et al., 2012b) the timing of sequential impulsive control of locomotion is consistent across tasks and subjects (d'Avella et al., 2003; Ivanenko et al., 2004, 2006; d'Avella and Bizzi, 2005; Cappellini et al., 2006). For example, walking and running show similarly patterned control of neural commands (Cappellini et al., 2006; Lacquaniti et al., 2012b) and become automatized motor gestures by experience, with primitive basic motor patterns which are innate (Lacquaniti et al., 2012a). When other tasks are added to a locomotion motor pattern, such as kicking during walking, additional modules and timing

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Abbreviations: ADD, adductor muscles; BF, biceps femoris; CoM, centre of mass; CoMp, CoM power; CoV, coefficients of variations; EMG, electromyography; EOB, external oblique; ESP, erector spinae; *Fx*, medial–lateral ground reaction force; *Fy*, anterior–posterior ground reaction force; *Fz*, vertical ground reaction force; GMA, gluteus maximus; GME, gluteus medius; M1, motor module 1; M2, motor module 2; M3, motor module 3; M4, motor module 4; M5, motor module 5; PER, peroneus longus; RAB, rectus abdominis; RF, rectus femoris; SSE, sum of squared errors; SST, total sum of squares; ST, semitendinosus; TA, tibialis anterior; TFL, tensor fascia latae; VAF, variation accounted for; VL, vastus lateralis; VM, vastus medialis; W-Abs, external work during absorption; W-Prp, external work during propulsion.

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activation signals are added in a linear manner maintaining the basic structure of impulsive control (Ivanenko et al., 2005).

In this study, we analyse the neuromuscular organization of more complex locomotor tasks than those previously analysed. In these tasks, the subjects are requested to suddenly change the direction of running by 90°. These tasks, also called cutting manoeuvres, are characterized by a change in the original direction of straight running, which may require changes in the motor patterns to perform negative work, discontinuing the forward displacement, followed by the generation of an additional laterally directed impulse against the ground (Rand and Ohtsuki, 2000).

We hypothesized that such complex tasks are still controlled by the same burst-like impulses of activations as in walking and running with their respective timing being related to the main events during the change in direction. Verification of this hypothesis would show that the sequential impulsive control observed during walking/running is a general control strategy for locomotion, valid also for more complex locomotor tasks. Given the need for precise timing in complex tasks, it was further hypothesized that cutting manoeuvres, which are less common tasks than walking and running, would show a greater timing variability in activation impulses across subjects and that this variability would explain the differences in task performance across subjects. Verification of this hypothesis would associate a precise functional meaning to the timing of the neural commands to activate muscle groups in order to accelerate or decelerate the body's centre of mass (CoM).

The aim of the study was to verify the two hypotheses of sequential burst activation of a low number of motor modules in the complex task analysed and association of the activation timing to the biomechanical goals during the motion. We provide this analysis for a large number of subjects to identify subject-specific differences in the performance of the analysed task and association of these differences with the timing of neural control.

EXPERIMENTAL PROCEDURES

Subjects

Twenty-two healthy men (age, 28 ± 4 years; body mass, 71 ± 10 kg; body height, 171 ± 7 cm) volunteered for the experiment. All subjects were recreational practitioners of team sports (soccer, basketball, handball, ice hockey). They had no known history of neurological or motor disorder. All subjects provided written-informed consent before participation and the procedures were approved by the Ethical Committee of Northern Jutland (N-20100042).

Experimental setup

The subjects were asked to perform repeated 90° cutting movements during a single session. The task consisted of running from 6 to 7 m away of a force platform, aiming to step with the right foot over the force platform, turn 90° to the left and continue running (Fig. 1). All subjects were right-footed, which was defined by dominance test (drop and kick a ball against a wall three times), therefore all analyses were performed considering the dominant limb. Each subject performed 10–15 cutting trials for familiarization being instructed to accelerate in a straight path towards the force platform and turn as fast as possible to the left. Adjustments on approaching running speed were necessary in order to ensure that subjects were performing the correct cutting trials as fast as possible. Subsequently, 10 cutting movements were recorded with a 40–60 s rest interval between trials to reduce the effects of fatigue. All subjects wore the same type of court shoes (FZ 2600W, FORZA®, Brønderslev, Denmark) in order to keep consistent conditions for all subjects. Additionally, 10 of the subjects were asked to perform jogging at a self-selected (comfortable) speed on an 8 m walkway. Subjects performed 10 trials with a 30-s rest interval between each trial.

Data collection

Kinematics. Retroreflective spherical markers were placed bilaterally each side of the subject to the skin overlying the following landmarks: calcaneus, first and fifth metatarso-phalangeal joint, lateral malleolus, lateral condyle; greater trochanter, anterior superior iliac spine, posterior superior iliac spine and acromion. In addition, one marker was placed in the seventh cervical vertebrae, upper and lower endpoint (suprasternal notch and xiphoid process of the sternum). Further markers were placed bilaterally on lower extremity segments: one on each thigh, four on the leg and one on each arm, serving as tracking markers to define the 3D motion. The positions of the markers were tracked with a motion analysis system with eight infrared digital video cameras (Oqus 300 series, Qualisys, Gothenburg, Sweden). Kinematic data were recorded with a sampling frequency of 256 Hz and synchronized with the electromyography (EMG) and kinetic recordings. Subjects wore full stretch pants covering the EMG cables to avoid movement artefacts.

Kinetics. The vertical (*Fz*), anterior–posterior (*Fy*) and medial–lateral (*Fx*) ground reaction forces were recorded at 1024 Hz by a three-dimensional force platform (AMTI, OR6-5, Watertown, MA) constructed over a hydraulic system (van Doornik and Sinkjaer, 2007). Software developed in Labview platform (MrKick II, Aalborg University, Aalborg, Denmark) was used for recording. Using a feedback electric circuit, the *Fz* force also served as trigger signal to initiate the force plate movement.

EMG. Surface EMG signals were recorded in bipolar derivations with pairs of Ag/AgCl electrodes (Ambu Neuroline 720 01-K/12; Ambu, Ballerup, Denmark) with 22 mm of centre-to-centre spacing. Prior to electrode placement the skin was shaved and lightly abraded. The EMG signals were amplified with a gain of 2000 (EMG-USB, LISiN; OT Bioelettronica, Turin, Italy), sampled at 2048 Hz, band-pass filtered (second-order, zero lag Butterworth, bandwidth 10–500 Hz) and 12 bits per sample A/D converted. A reference electrode was placed on the right wrist. The EMG signals were recorded from the following muscles of the right side according to the SENIAM recommendations (Hermens et al., 2000) and previous literature (Ivanenko et al., 2006): tibialis anterior (TA), peroneus longus (PER), soleus (SOL), gastrocnemius medialis (GM), vastus medialis (VM), vastus lateralis (VL), rectus femoris (RF), biceps femoris (BF), semitendinosus (ST), adductor muscles (ADD), gluteus medius (GME), gluteus maximus (GMA), tensor fascia latae (TFL), erector spinae at L1 (ESP), rectus abdominis (RAB) and external oblique (EOB).