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Stimulation site and phase modulation of the withdrawal reflex during gait initiation

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HIGHLIGHTS

- During gait initiation the nociceptive withdrawal reflex is modulated by posture and stimulation site.
- The nociceptive withdrawal reflex responses are largest during heel off and after stimulation of the arch of the foot.
- The nociceptive withdrawal reflex modulation followed a functional principle, which may be exploited in rehabilitation of the gait initiation process.

ABSTRACT

Objective: To investigate how the nociceptive withdrawal reflex (NWR) is modulated during gait initiation.
Methods: The NWR was elicited in ten subjects using electrical stimulation at four sites in the right foot during symmetrical stance (50% of body weight on each foot) or while performing the first step during gait initiation: either during heel off (HO, 20% of body load on the starting leg) or heel contact (HC, 80% of body load on the starting leg in the first step). Kinematics and EMG responses from major muscles of the ipsilateral leg were recorded.
Results: The NWR was modulated by stimulation site in all muscles except Soleus. The NWR responses elicited after stimulation of the arch were significantly larger than those evoked at all other sites in Tibialis Anterior, Rectus Femoris, and Vastus Lateralis. At the hip joint, the largest flexion was obtained during HO, whereas the smallest flexion was observed during HC, both following stimulation on the arch of the foot.
Conclusions: The NWR responses were modulated to maintain balance and continue the development of the gait initiation process.
Significance: The NWR modulation followed a functional principle, which might allow a functional use in rehabilitation strategies.

1. Introduction

Muscular activity, neural mechanisms, and biomechanical forces are highly integrated in the gait initiation process (GIP) (Mann et al., 1979). In this complex process, forces generated by the legs serve to limit postural perturbations and provide forward propulsion. However, in patients with Parkinson's disease (PD) or stroke, this process is sometimes disrupted (Hesse et al., 1997; Hass et al., 2005). In particular, people who suffered a stroke often have problems generating force in the starting leg and difficulties to load the limbs symmetrically during gait initiation (Brunt et al., 1995). As a consequence, gait initiation forces and momentums must be generated by the stance leg (Brunt et al., 1995) causing balance problems and difficulties when transitioning from quiet stance to steady-state dynamic gait.

Functional electrical stimulation can be used to obtain muscle contractions (see review (Lyons et al., 2002)). Electrical pulses are used to activate motor nerves that generate an action potential leading to direct muscle activation, allowing the possibility of controlling paralyzed muscles (Fuhr et al., 2008). Electrical stimulation can also be used to evoke reflexes, like the nociceptive withdrawal

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reflex (NWR) (Spaich et al., 2006). The NWR can be used to activate a synergistic set of muscles in a more functional manner than by electrical stimulation of individual motor nerves and to activate muscles that are difficult to access by surface electrodes like the hip flexors. The NWR has been successfully used to evoke ankle dorsiflexion during the swing phase by afferent stimulation in stroke individuals (Quintern et al., 2003). The reflex produces also flexion of the hip and knee during gait in hemiparetic patients when elicited appropriately (Quintern et al., 2003; Spaich et al., 2006). Swinging of the leg can be achieved even in subjects with spinal cord injury using the NWR (Nicol et al., 1995).

In symmetrical standing, larger reflexes are obtained at higher degrees of unloading (Serrao et al., 2012b). In the GIP, as soon as the starting leg is unloaded and prior to any movement, the excitability of the NWR in hip and knee flexor muscles is also increased (Serrao et al., 2012a). Previous studies have been carried out during rhythmic walking (Spaich et al., 2004) and during symmetrical standing (Andersen et al., 2003) to characterize stimulation site dependencies for the NWR during these two stable, steady-state conditions. However, an understanding of the stimulation site and phase dependencies during the GIP is lacking. The GIP is a biomechanically relatively unstable transition from standing to walking and hence the influence on the spinal reflex organization in this phase is not known, e.g. is forward propulsion, balance control or effective limb withdrawal governing the net reaction to a stimulus perturbation applied at different skin sites? A better understanding of the behavior of the NWR during the GIP is needed to be able to administrate an electrical stimulation strategy to help patients with neuromuscular pathologies during gait initiation (Berardelli et al., 2001).

The purpose of the present work was to explore the behavior of the NWR during the transition from standing to walking in healthy subjects. The kinematics and electromyographic activity (EMG) of five muscles in the starting leg were examined following stimulation of the sole of the foot during gait initiation.

2. Materials and methods

2.1. Participants

Ten healthy volunteers (8 males, 2 females, age range: 19–31 years). Exclusion criteria: left-leg dominance or history of neuromuscular or osteoarticular disorders. The protocol of the study was approved by the local ethical committee (case number VN2007-0026) and was in accordance with The Declaration of Helsinki. All volunteers gave their written informed consent before participating in the study.

2.2. Evoking the nociceptive withdrawal reflex

The nociceptive withdrawal reflex was elicited by transcutaneous electric stimulation delivered in random order to three sites in the sole of the right foot: the third metatarsophalangeal joint (forefoot), the medial arch of the foot (arch), and the plantar side of calcaneus (heel), and one site on the posterior side of calcaneus (post-heel). The stimulation was delivered through self-adhesive electrodes (AMBU Neuroline 700, Denmark). A reference electrode (7×10-cm electrode, Pals, Axelgaard Ltd., USA) was placed on the dorsal aspect of the foot (Emborg et al., 2009). Each stimulus consisted of a constant current pulse burst of five individual 1-ms pulses delivered at 200 Hz.

Pain thresholds for the four stimulation sites were determined with the volunteers in seated position, using a staircase method consisting of a series of increasing and decreasing stimuli. After each stimulus the volunteers rated the evoked sensation as non-painful or painful. When the stimulus was non-painful the intensity was increased until it was painful, then, the stimulus intensity was decreased until it was non-painful. This procedure was repeated three times and the pain threshold was determined as the average of the three painful intensities. Subsequently, the stimulus intensities were obtained as a multiple of the pain thresholds detected at each electrode site. The multiplication factor was the same for all sites and was determined based on the evoked NWR with the subjects in symmetrical standing posture to ensure a clear and stable reflex.

2.3. Outcome measures

2.3.1. EMG responses

EMG was acquired from tibialis anterior (TA), soleus (SOL), vastus lateralis (VL), rectus femoris (RF), and biceps femoris (BF) of the ipsilateral leg. For VL, RF, and BF a single differential configuration was used to record the EMG signals. To minimize crosstalk contamination, EMG from TA and SOL was acquired using a double differential configuration (Frahm et al., 2012). The recordings were obtained using surface electrodes (Neuroline 720, AMBU, Denmark), amplified, band-pass filtered (0.5–500 Hz, 2nd order), sampled at 2 kHz, displayed, and stored for further analysis.

2.3.2. Kinematic responses

Three goniometers (Biometrics Ltd., typeSG150 and SG110/A, Gwent, UK) were mounted on the lateral side of the ankle, knee, and hip joints of the right leg to record movements in the sagittal plane. The goniograms were sampled at 2 kHz, displayed, and stored together with the EMG recordings.

A force plate (AMTI, type OR6-7, USA) was used to measure the body load of the starting leg and to detect displacement of the center of pressure (CoP) during gait initiation.

2.4. Postures

The subjects were stimulated on the right foot during symmetrical standing or while performing the first step during gait initiation. The specific postures were:

- Symmetric standing, with both feet inside the force plate; 50% of body load on each foot (ST).
- Heel off (HO), with 20% of the body load on the starting leg, starting to walk with the right leg.
- Heel contact (HC), with 80% of the body load on the starting leg during the first contact with the ground; starting to walk with the right leg.

2.5. Experimental procedure

Before starting the actual reflex recordings, the subjects were instructed on how to maintain the different postures helped by visual feedback. Based on the force plate measures, the visual feedback consisted of a small square on a computer screen depicting the CoP. Additionally, the square changed color according to the weight load from red (0% of body weight) to blue (100% of body weight), but at 50% of the body weight of the subject, the square's color changed to black in order to be easily distinguishable. The screen to visualize the feedback was placed at a comfortable height in front of the subject (Fig. 1). At the beginning of the experiment, subjects stood upright and barefoot at the center of the force plate, with their feet parallel and the inner edges of their heels approximately 20 cm apart in order to measure body weight and to set the moving square to zero position and blue color (100% of body load).

To obtain the ST posture, the subjects were requested to keep the moving square within an area on the screen that corresponded