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Interaction against different environmental dynamics during a leg extension task is controlled by temporal rather than amplitude scaling of muscular activity

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ABSTRACT

Force exertion against different mechanical environments can affect motor control strategies in order to account for the altered environmental dynamics and to maintain the ability to produce force. Here, we investigated the change of muscular activity of selected muscles of the lower extremities while the participants interacted with an external mechanical device of variable stability. Twenty-five healthy participants exerted force against the device by performing a unilateral ballistic leg extension task under 1 or 3 degrees of freedom (DoF). Directional force data and electromyographic responses from four leg muscles (TA, VM, GM, PL) were recorded. Muscle responses to the altered experimental conditions were analyzed by calculating time to peak electrical activity (TTP), peak electrical activity (PEA), slope of EMG-signal and muscle activity. It was found that neuromuscular system adjustments to the task are expressed mainly by temporal (TTP) rather than amplitude (PEA) scaling of muscular activity. This change was specific for the investigated muscles. Moreover, a selective increase of muscle activity occurred while increasing external DoF. This scheme was accompanied by a significant reduction of applicable force against the device in the unstable 3 DoF condition. The findings suggest that orchestration of movement control is linked to environmental dynamics also affecting the ability to produce force under dynamic conditions. The adjustments of the neuromuscular system are rather temporal in nature being consistent with the impulse timing hypothesis of motor control.

1. Introduction

The well-coordinated use of muscles during all kinds of activities is known to be a prerequisite for motor control strategies facing the redundant nature of the neuro–musculo-skeletal system. Because of the redundancy, the interaction with various environmental conditions constitutes a requirement for an adaptive control of stiffness properties of the involved joints. These motor control strategies provide robustness to motor output variability and perturbations from the environment (Franklin et al., 2003). However, from biomechanical studies it is well known that neuromuscular control patterns change in response to different stability conditions and affect the forces transmitted to the surrounding (Bober et al., 1982; Kornecki and Zschorlich, 1994; Kornecki et al., 2001). We have recently identified distinct intermuscular temporal activation patterns and selective gain changes of the involved muscles as cardinal determinants of these neuromuscular adjustments of the stabilization process (Wuebbenhorst and Zschorlich, 2011) as well as changes in neural control strategies (Holl and Zschorlich, 2011). These studies support the idea by Rancourt and Hogan (2009) that force exertion against the mechanical environment can destabilize motion and compromise on the ability to exert force. Franklin et al. (2003) distinguished control strategies of stable and unstable tasks pointing out that unstable tasks require muscular activation levels above and beyond that usually occurring with the movement. However, the increase in muscular activation due to stabilization often cannot be used for effective force transmission to the surrounding as evidenced by decreased peak forces (Bober et al., 1982; Wuebbenhorst and Zschorlich, 2011) or by reported differences for predicted joint stiffness from net joint torque necessary for producing the movement under unstable conditions (Franklin et al., 2003). Therefore, the instability created by the muscular force itself may limit the force magnitude (Rancourt and Hogan, 2001a,b). Additionally, the ability to coordinate muscle groups for producing rapid, goal-directed movements is indispensable and was shown to be a major factor for performance losses in rapid force production in the elderly (Barry et al., 2005). However, in order to stabilize movements under varying conditions the motor system uses stiffness regulation processes of the involved joints (Rancourt

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and Hogan, 2009). As shown by Hunter and Kearney (1982) stiffness properties scale with muscular activation level. Nevertheless, when stabilizing a joint, co-contraction of the agonist–antagonistic system provides a means for counteracting a destabilizing force and alters joint stiffness (Heitman et al., 2011). However, as shown by Milner et al. (1995) muscle activation capability can be reduced by 50% when antagonistic cocontraction is required. The latter fact highlights the importance of a proper coordination strategy.

Hence, we concluded that the stabilization process (and consequently the maintenance of the ability to exert force) is a manifestation of movement coordination (Wuebbenhorst and Zschorlich, 2011). Accordingly, the mentioned studies showed that the mechanical coupling of a limb and an external object causes neuromuscular system adjustments to the actual task and therefore to its biomechanical demands. Nevertheless, the mechanisms to achieve a precise control of the stabilization process in order to control the exerted force (Rancourt and Hogan, 2009) are not fully understood. Based on the fact that neuromuscular responses to mechanical instability are coupled to environmental dynamics, we can expect that control strategies such as muscle activation patterns are constrained by the particular mechanical condition of the task (Rancourt and Hogan, 2001a,b; Pinter et al., 2011). As pointed out by van Soest and van Galen (1995) the identification of such constraints is a prerequisite for proper understanding of the coordination of multi-joint movements. However, the aforementioned studies investigated either movements of the upper extremities or controlled, slow movements. The latter approach requires completely different use of stabilization-related and propulsive muscles as compared to fast movement velocities (Hagood et al., 1990). Here, we extend previous studies by investigating the effects of environmental stability changes during ballistic (high effort) multi-joint movements of the lower extremities (see also Wuebbenhorst and Zschorlich, 2012).

Consequently, this study is conceptually based on changes in the mechanical nature of the interaction against an external object. We assessed changes in the mechanics of muscular control by evaluation of intramuscular muscle activation characteristics. Having regard to previous observations of our laboratory, we hypothesized that (1) the force output would decrease with increasing external Degrees of Freedom (DoFs) and (2) that intramuscular coordination is adjusted to the type of mechanical interaction.

2. Materials and methods

2.1. Participants

The study involved 25 male volunteers (age: 24.8 ± 3.2 SD, height 180.2 cm ± 4.9 SD, weight 82.7 kg ± 6.4 SD). At the time of the study, none of the participants had ever experienced any injuries involving their lower extremities. The institutional ethics committee approved the experiments and all subjects gave written consent after being informed about the procedures of the experiment.

2.2. Apparatus

The subjects were asked to produce maximum force by performing an unilateral extension movement with their right leg in a sitting posture. The test apparatus used is shown in Fig. 1 and will be referred to as 'movement sled'. The sled moved on an inclined plane ($\alpha = 30°$) with the movable parts having a weight of 18.2 kg. A counterweight of 37.5 kg (Pos. 2 in Fig. 1) was attached to the sled using steel cables and pulleys. The subjects were instructed to exert force against a footplate which varied in the degree of instability (Pos. 1 in Fig. 1) to create different stabilizing conditions. In these experiments we used two dynamic conditions in which the sled was in an unhitched configuration. By using a rigid footplate (consisting of a block of wood), the subjects were exposed to 1 DoF. This condition allowed for movements along with the leg extension (*z*-direction in Fig. 1) and was considered to provide a stable interaction. In the second condition an unstable footplate was employed which was connected to the sled by a ball joint. Consequently, this condition caused 3 DoF, which comprised horizontal, rotational and translational movements that allowed for inversion/eversion and dorsal/plantarflexion of the ankle. The center of the ankle joint was aligned with the center of rotation of the ball joint of the device (footplate). This configuration was checked before every 3-DoF-trial and ensured the same point of contact between trials.

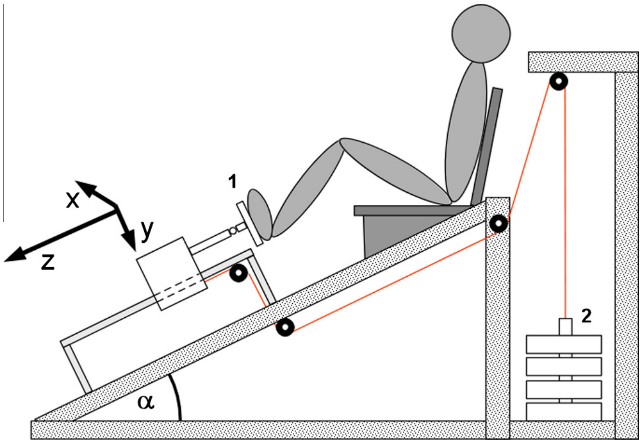

Fig. 1. The apparatus used in the present experiments (referred to as 'movement sled'). The sled moves on an inclined plane (angle α=30°). The footplate (pos. 1) was changed in order to create different experimental conditions. The counterweight (pos. 2) was set to 37.5 kg. Movement dimensions are indicated by arrows.

2.3. Protocol

The experiment was conducted in one session. Before performing the investigated movements, subjects completed a 5-min warm-up period on a treadmill (at 6 km/h) and 5–10 practice trials on the sled. All subjects were naïve to the test. In each condition (1 or 3 DoF) a block of five trials had to be completed, adding up to a total of 10 successful trials in the two conditions combined. The order of the tested conditions was randomized. This experimental approach allows to rule out effects of fatigue or the influence of testing order. The participants were asked to perform a ballistic, maximal leg extension (force production) movement against the sled. The criterion of a maximal effort in minimal time in each trial was eminent and each participant was constantly encouraged to do so. Participants were provided with constant verbal feedback about their performance and the force–time curve was checked in order to secure performance quality. For each trial the initial sitting position and the position of the limb (right leg) was checked so that each subject started with a knee and ankle angle of 90°. The correct limb arrangement on the sled was checked by the use of a goniometer. The seat was adjustable to the height of the subjects, which secured intersubject comparability. During data acquisition the subjects were to rest at least 30 s between trials to rule out potential fatiguing effects. Trials not matching our criteria of ballistic force production or trials with irregularities (e.g. slipping from the plate) were discarded from further analyses (judged by visual inspection of force–time curve).