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UNINTENDED HAND MOVEMENTS AFTER ABRUPT CESSATION OF VARIABLE AND CONSTANT OPPOSING FORCES

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Abstract—Humans are highly efficient in moving in a world of variable resistive forces which result, e.g., from different masses of objects or different directions of movements relative to gravity. However, the underlying mechanisms are challenged when an opposing force is suddenly removed. The resulting involuntary movements are known as accident risks in everyday life. We studied their characteristics upon abrupt cessations of opposing forces of 1, 2, and 4 N which were presented in a series of variable or constant forces. The characteristics of the involuntary hand movements are largely determined by the mechanical impedance of the limb. The involuntary movements are oscillatory in nature, and their amplitude increases with stronger opposing force. Limb impedance is modulated both in a reactive and in an anticipatory manner. The reactive modulation occurs during each involuntary movement as a consequence of the neural responses elicited by the rapid limb acceleration consequent upon the cessation of the opposing force. Anticipatory modulation of limb impedance may serve to produce similar involuntary movements in spite of different opposing forces. The modulation is thus stronger with variable forces, where differences between resulting involuntary movements can be experienced more easily, than with constant forces. © 2013 IBRO. Published by Elsevier Ltd. All rights reserved.

Key words: limb impedance, impedance control, anticipation.

INTRODUCTION

Humans move in a world of variable mechanical impedance, and this variation is generally taken into account in motor control. A major source of variable resistance is gravity. Aimed movements with and against gravity have similar kinematics (Papaxanthis et al., 1998), but grossly different patterns of muscle activity (Virjii-Babul et al., 1994). When a hand-held object is moved in different directions, grip forces are well-adjusted to gravitational forces (Flanagan and Wing, 1995; Hermsdörfer et al., 2000), and collisions of the object with a surface are accompanied by sharp increases of grip force before and briefly after the impact (White et al., 2011). A second major source of variable resistance is the mass of objects. Movements with objects of unknown mass are only briefly perturbed and almost instantaneously adjusted (Bock, 1990, 1993; Johansson and Westling, 1984; Smeets et al., 1995). When objects are suddenly placed in the hand or removed from it, anticipatory and reactive responses dampen or even abolish the mechanical effects (Dufossé et al., 1985; Lacquaniti and Maioli, 1989). The present study is concerned with a less frequent source of variable resistance, which, however, produces rapid involuntary movements that can result in injuries. This is the abrupt cessation of a force that opposes a voluntary movement, as it occurs in cutting materials. The dangers of this type of abruptly changing resistance are well-known in everyday life and are reflected in the safety rule of cutting in a direction away from one's own body parts.

In an anticipatory mode, the sensori-motor systems of the brain can deal with variable environmental forces in two different ways, impedance control and internal models of the environmental dynamics (cf. Franklin et al., 2003). Impedance control, that is, modulation of the impedance of the moving limb, is suited for unpredictable or complex variations of environmental forces as they occur in operating simple tools, for example (cf. Heuer and Sülzenbrück, 2012). It goes along with metabolic costs because in general it requires co-contractions of antagonistic muscles. Internal models, on the other hand, enable more economic control when variations of environmental forces are predictable.

In principle impedance control and internal models equip the motor-control systems with the means to produce movements that are essentially unaffected by variable resistance. However, in the case of an abrupt cessation of an opposing force these mechanisms are challenged. High levels of impedance can be reached before the abrupt change occurs, but only for rather small opposing forces will they suffice to prevent the rapid involuntary movement. With perfect predictability, even the most accurate internal model will not allow an instantaneous compensatory adjustment of active forces. Thus, an involuntary movement will begin, and it will be stopped by means of different mechanisms. These mechanisms should be both mechanical and neural, and they should not only be anticipatory, but also reactive.

A basic mechanism of stopping involuntary movements, which are triggered by the abrupt cessation

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of an opposing force, should be inherent to the mechanical characteristics of the limb. Consider the simplified representation of a muscle-joint structure as a second-order system (cf. Winters and Stark, 1987), for which an opposing force F_e is abruptly switched off at time $t = 0$:

$$\begin{aligned} m\ddot{x} + b\dot{x} + k(x - x_v) + F_e = 0 \quad \text{for } t < 0 \\ m\ddot{x} + b\dot{x} + k(x - x_v) = 0 \quad \text{for } t > 0 \end{aligned} \tag{1}$$

In these equations m is inertia, *b* is viscous damping, and *k* is stiffness. The position of the end effector is *x*, its velocity is $\dot{x}$, and its acceleration is $\ddot{x}$. The equilibrium position of the system is x_v, and F_e is the opposing force. Fig. 1 shows random samples of the behaviour of this system for $t > 0$ and three different strengths of the opposing force F_e, 1, 2, and 4 N. The parameters m, b, and k were chosen in the range of the estimates given in Table 1 of Tsuji et al. (1995) for a posture and a direction of movement somewhat similar to the hand posture and direction of movement in the present study. Means (and standard deviations) were: $m = 1.7$ (0.1) kg, $b = 18$ (3) N s/m, $k = 370$ (60) N/m. To model the voluntary movement against the opposing force, the equilibrium position moved with a velocity of 0.045 (0.015) m/s, which is roughly the movement velocity at the end of the force field in the present study, and stopped abruptly at $t = 0$. Thus, there was no more voluntary movement component in the examples of Fig. 1.

From Fig. 1 it is apparent that the mechanical characteristics of muscle-joint structures are sufficient to stop the involuntary movements, provided that the voluntary movements that were executed against the opposing force are stopped. From the mechanical characteristics certain predictions for the involuntary movements can be derived. Basically the involuntary movements should have the characteristics of damped oscillations. First, when the opposing force is switched off, there should be a rapid initial increase of the amplitude that is stronger for a stronger opposing force than for a weaker one. Second, there should be a reversal movement after a maximum has been reached, and again its amplitude should be larger for the stronger than for the weaker opposing force. The amplitude reaches an asymptote that, in terms of the model, corresponds to the equilibrium position of the system. Finally, the variability of movement characteristics should generally increase with higher opposing force.

This list of predictions for involuntary movements triggered by the abrupt cessation of an opposing force is based on a simplified mechanical model. Beyond the simplifications made for the formal model, additional predictions accrue. As compared with real movements, a first simplification is the one-dimensionality of the model. In contrast, real involuntary movements without mechanical constraints are three-dimensional. They are likely to be curved rather than straight because of the anisotropy of limb impedance (e.g., Tsuji et al., 1995), which results in deviations between the direction of force and the direction of movement.

A second simplification of the mechanical model is the neglect of reactive neural responses to the offset of the opposing force. The sudden acceleration of the arm leads to shortening of the agonists and lengthening of the antagonists, which elicits unloading reflexes and stretch reflexes. These counteract the lengthening of the antagonists. The first EMG component, M1, is seen as early as 25–50 ms after the stretch and generated via the monosynaptic connection of muscle-spindle afferents to the spinal motor neurons (Pearson and Gordon, 2000). The second EMG component, M2, follows 50–75 ms after the stretch and is likely to be mediated by the motor cortex. Due to this involvement of supraspinal structures, M2 can be centrally modulated depending on the task (cf. Gielen et al., 1988) or the predictability of the reflex-triggering stimulus (Al-Falahe and Vallbo, 1988; Crago et al., 1976). Sometimes a third component, M3, is mentioned, which is also called triggered response (Mutha et al., 2008) and occurs around 80–120 ms after the abrupt stretch. Crago et al. (1976) demonstrated voluntary suppression of this component following corresponding instructions. Reflex responses should be followed by

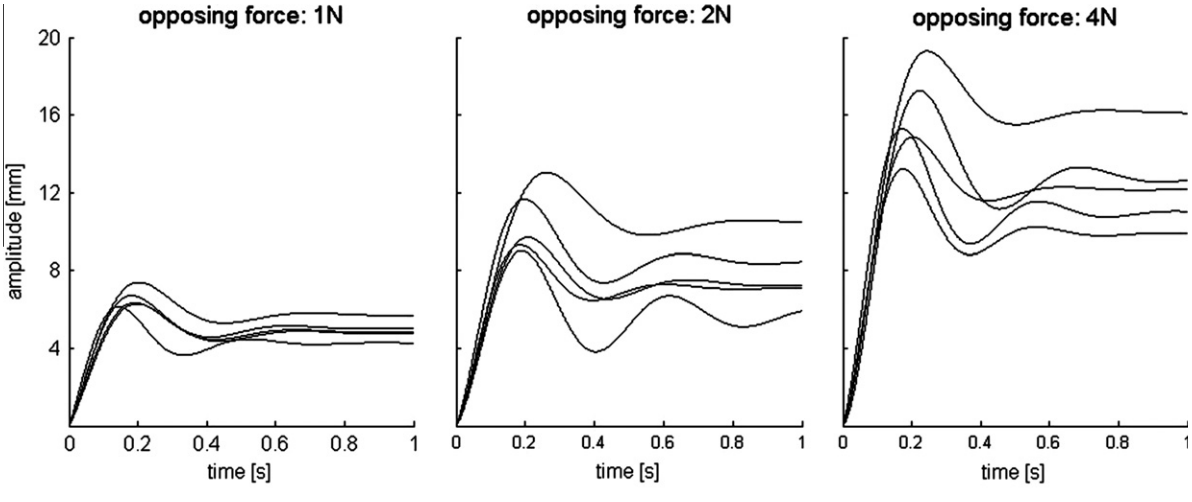

Fig. 1. Responses of a linear second-order system with randomly chosen parameters to abrupt cessations of opposing forces of different strengths.