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Adjustments after an ankle dorsiflexion perturbation during human running

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ABSTRACT

In this study we investigated the effect of a mechanical perturbation of unexpected timing during human running. With the use of a powered exoskeleton, we evoked a dorsiflexion of the right ankle during its swing phase while subjects ran on a treadmill. The perturbation resulted in an increase of the right ankle dorsiflexion of at least 5°. The first two as well as the next five steps after the perturbation were analyzed to observe the possible immediate and late biomechanical adjustments. In all cases subjects continued to run after the perturbation. The immediate adjustments were the greatest and the most frequent when the delay between the right ankle perturbation and the subsequent right foot touch-down was the shortest. For example, the vertical impact peak force was strongly modified on the first step after the perturbations and this adjustment was correlated to a right ankle angle still clearly modified at touch-down. Some late adjustments were observed in the subsequent steps predominantly occurring during left steps. Subjects maintained the step length and the step period as constant as possible by adjusting other step parameters in order to avoid stumbling and continue running at the speed imposed by the treadmill. To our knowledge, our experiments are the first to investigate perturbations of unexpected timing during human running. The results show that humans have a time-dependent, adapted strategy to maintain their running pattern.

1. Introduction

Running is one of the most popular recreational activities. This could explain why the biomechanics of normal running are so well documented [1,2]. Although in the real world humans must negotiate various perturbations during running, little is known about the way they do it.

In walking, the effects of unexpected perturbations such as slipping [3], tripping [4], obstacle avoidance [5,6], loss of ground support [7] or unexpected compliant surface [8] have been investigated. For any given perturbation, rapid and appropriate adjustments have been observed allowing the subjects to avoid falling and continue walking. Perturbations such as a mechanically evoked ankle dorsiflexion have also received a lot of interest during walking [9,10]. The amplitude of the plantar-flexor muscles reflex responses was investigated but little attention was paid to the walking pattern adjustments realized by the subject after that perturbation.

In running, Grimmer and colleagues [11,12] measured the biomechanical adjustments made by subjects running over an uneven track which incorporated a clearly visible force plate of adjustable height. The runners maintained their running pattern by adjusting their leg contact angle and ankle joint stiffness to the height of the vertical step.

In animals, the strategies used to negotiate an unexpected perturbation during running have been discussed over the last 10 years [13–16]. Jindrich and Full [13] showed that a running cockroach pushed to one side, recovered within two strides and continued running on its original path. Daley and colleagues [14–16] investigated the reactions of guinea fowl to an unexpected drop in terrain height during running. The drop of 8.5 cm (approximately 40% of the leg length) was dissimulated by a thin paper. In all experimental trials, the guinea fowls recovered and continued running at about the same preferred speed as before; in only one trial, an animal stumbled, but without falling.

Daley [17] and Alexander [18] consider that dynamic stability is the ability of a system to continue a pattern of motion in the face of small disturbances. This ability has been observed after an unexpected perturbation in human walking [3–8] and animal locomotion [13–16]. To our knowledge, no study has investigated unexpected perturbation during human running.

In this study, we investigated the adjustments made to the running pattern after an ankle perturbation of unexpected timing, by measuring the angular position of the ankle and the ground reaction forces. We used an innovative powered ankle-foot exoskeleton to mechanically evoke ankle dorsiflexion at random timing inside the swing phase. We observed whether the adjustments were modulated as a function of the perturbation

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timing. The two steps following the perturbation were analyzed for the immediate adjustments made by the subject, and the subsequent five steps were analyzed for the late adjustments.

2. Methods

2.1. Subjects

Seven healthy young men (age = 26.2 ± 2.2 years, body mass = 75.6 ± 9.1 kg, height = 1.81 ± 0.03 m) participated in this study. All subjects were free of lower leg injuries at the time of the experiment. Subjects were informed of the experimental conditions and provided their written consent to participate. Experiments were performed according to the Declaration of Helsinki and approved by the local ethics committee.

2.2. Materials

All subjects ran on an instrumented treadmill at a speed of 2.8 m s^{-1} while wearing regular running shoes and equipped with a powered exoskeleton on their right leg (Fig. 1A and B).

This new device, inspired by that of Andersen and Sinkjær [19], was designed to deliver a well-defined perturbation to the right ankle joint while the subject is running on the treadmill. It consists of two carbon fiber shells, custom-made for each subject, placed around the foot and the lower leg. The shells are linked by a joint pivoting at the center of rotation of the ankle and allowing only dorsi-plantar movements. An optical encoder in the pivot (1 kHz sampling rate, Avago Technologies®, HEDS-9200) measured the angular position of the ankle (°). A clutch and actuator (SEW®), connected to a servomotor (Parker Compumotor® AT6250) by Bowden cables, could flex the ankle at speeds up to 600° s^{-1} with a

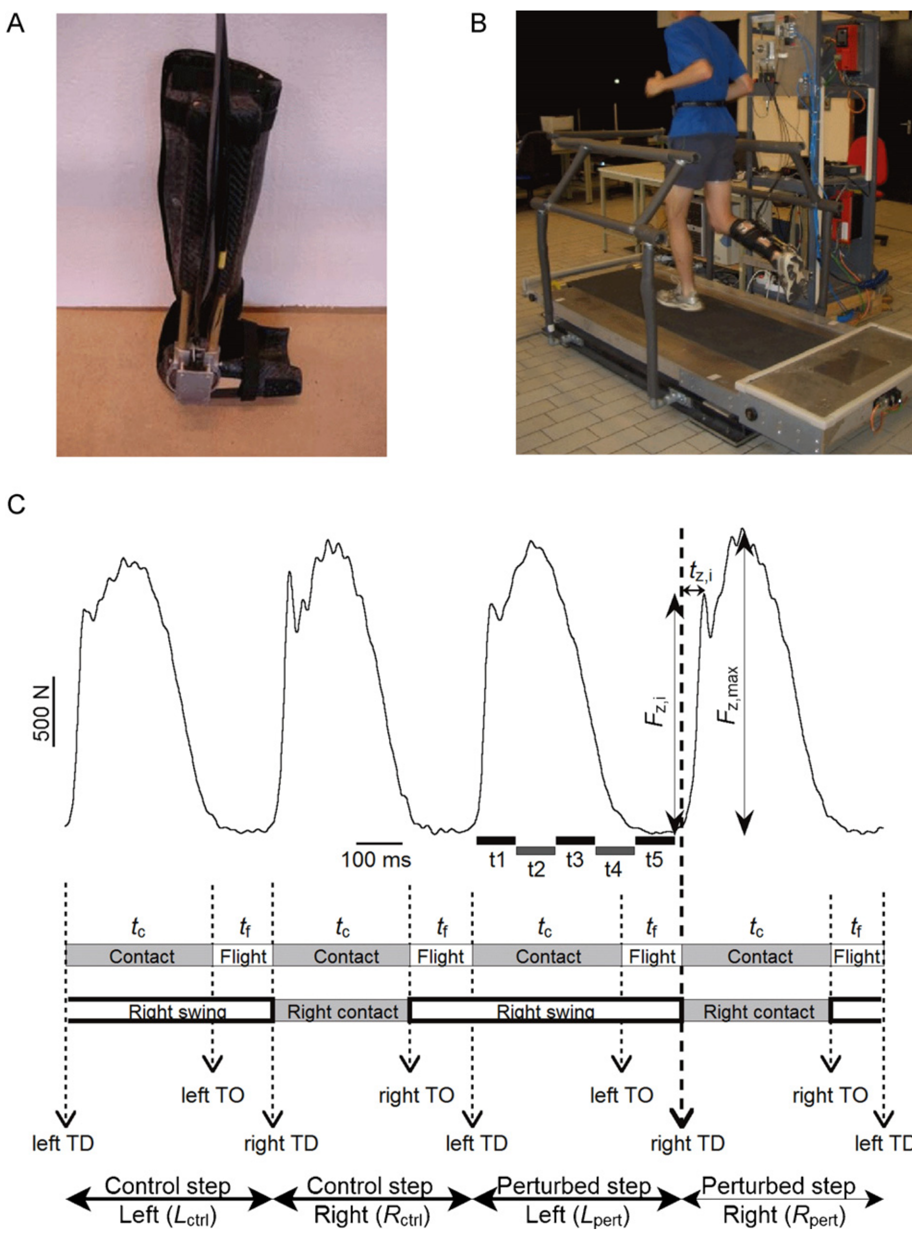

Fig. 1. (A) Powered exoskeleton designed to deliver a perturbation to the right ankle joint during running. Two carbon fiber shells around the foot and the lower leg are linked by a hinged joint pivoting at the center of rotation of the ankle. (B) Subject with exoskeleton running on the treadmill. (C) Typical trace of the vertical ground reaction force (F_z, N) of one subject; only the first four steps of the sequence, including the control steps (L_{ctrl} and R_{ctrl}) and the perturbed steps (L_{pert} and R_{pert}), are shown. TD = touch-down of a foot. TO = toe-off of a foot. *L* or *R* for left or right, ctrl or pert subscripts for control or perturbed steps. The vertical interrupted line indicates the first TD following the perturbation (right TD). The vertical dotted lines indicate TD or TO. The white boxes represent the swing phases while the grey boxes represent the contact phases. Perturbations were applied to the right ankle during its swing phase, more precisely during the contact phase of the left foot or the flight phase preceding the right TD, *i.e.* during L_{pert} as defined at the bottom of Fig. 1C. The perturbations were classified into five timing groups as shown: t1, t2, t3, t4 and t5, see Section 2 for details. The parameters t_c, t_f, $F_{z,max}$, $F_{z,i}$ and $t_{z,i}$ are described in the text.