

Energy analysis of gait perturbations

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Introduction

During gait, the human being is subject to all kinds of perturbations, sometimes ending in a fall. The most common real-life gait perturbations can be categorized as: slip, stumble and push (Winter 1995). In the slip the landing foot slides accidentally, in the stumble, the swinging foot strikes something and in the push, the subject is jostled. The question that remains is: What discriminating factors determine whether we fall or we do not fall?. The analysis of the reaction to gait perturbations provides a way to measure gait stability performance. The goal of this study is to identify strategies to avoid falling, and, ultimately, to find the limitations that a person has to execute this recovery strategies. To do so, an experiment was performed imposing a stumble on the treadmill with four stumbling conditions: During early swing with short and long duration of the perturbation, and during mid and late swing with short duration (Forner Cordero et al. 2001). Two main factors condition the response, one is the instant of the perturbation with respect to the gait cycle (e.g., early swing) and the other is the impulse of perturbation input to the body, that is, the amplitude of the perturbing force and the duration of the perturbation. One way to quantify the perturbation is to measure the perturbing energy and to analyse how the subjects handles this change of energy to avoid falling. This step is crucial in order to find the stability limits of gait with respect to perturbations.

Methods

An experimental setup to simulate stumbling was designed with the following requirements: a) the perturbation should be unexpected for the subject, b) the gait cycle instant of the perturbation should be controllable, c) the perturbation force and duration should be controllable, d) and the experiment should be safe for the subject. A rope was attached to the left leg, in such a way that can be blocked, braking the forward swing of the leg and inducing a stumble on the treadmill (Forner Cordero et al., 2000). The measurement setup consists of: a) blocking device based on compressed air, b) triggering control, using footswitches processed on-line, c) treadmill, d) safety frame and harness, e) VICON for motion measurements. Five healthy young adults were unexpectedly perturbed while walking comfortably at 4 km/h on the treadmill. The duration of the blocking was changed from 100 ms to the whole swing duration and were applied at the early, late and mid-swing of the left leg. Kinematics responses of the lower limbs were recorded along with the perturbing force. The timing of the gait cycle was analyzed on-line in order to synchronize the perturbation instant. This was accomplished by means of footswitches placed on the foot sole. A safety frame attached to a harness prevented the subject from falling. The motion data were analyzed to calculate the kinetic and potential energy of the segments from their position, velocity and acceleration, following the procedures described by Koopman (1995).

Results

Consistent changes in the step parameters (length and duration) and in the joint angles and joint angular speeds were found due to the different perturbations, allowing to describe certain response strategies depending on the perturbation onset and duration. For early swing, delayed lowering or elevating strategies were performed. For mid and late swing a lowering strategy emerged (Eng et al. 1994, Schillings et al. 2000, Forner Cordero et al. 2001). The limitations in the recovery also depend on the strategy. In a lowering one, the possible limitation is to perform a quick recovery step, keeping up with the treadmill speed. In an elevating strategy, the possible limitation is to perform a long step resisting the perturbation (Forner Cordero, 2001). The recovery strategies can be analysed from the point of view of changes in the segment energies. The results concerning the early and late swing short duration perturbations are presented. Figure 1 shows in different columns, the total, the potential and kinetic energies of the left tibia and trunk (HAT) segment for a normal stride, for a perturbed one and for a recovery stride. The stumble causes a decrease in the energy of the swinging leg. Immediately after the perturbation ceases, the total energy of the tibia increases rapidly. Both the increase and decrease of the tibial energy are due to the changes in the kinetic energy, although the potential energy shows higher

values than normal. The changes in the trunk energy are larger than of the tibial energy. The potential energy of the trunk is similar to the normal gait values, and only increases at the end of the perturbation.

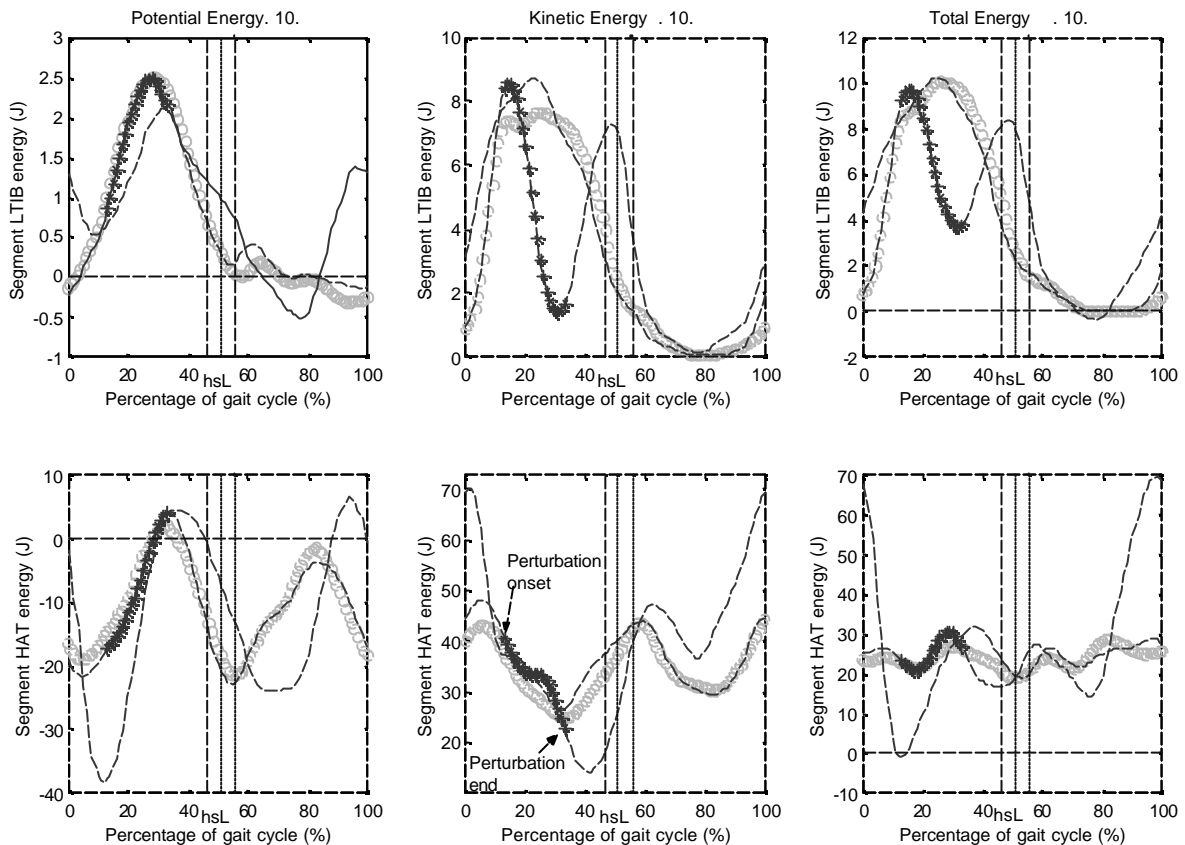


Figure 1: Potential, kinetic and total energies of the left (perturbed) tibia (LTIB) and trunk (HAT) segments of an early swing perturbation with elevating strategy. Three strides: normal (circled grey), perturbed (solid thin line) and recovery (dashed line) are plotted with respect to the percentage of gait cycle (consecutive right heel strikes). The perturbation is shown by asterisks. Vertical lines indicate left heel strikes.

The kinetic energy of the trunk is similar to normal during the perturbation, but decreases markedly after the perturbation ends. This means that the trunk is losing speed with respect to the treadmill. This is compensated by a large increase of kinetic energy at the end of the right step, that is related to a quick step to compensate for the previous speed loss. In the late swing disturbance, it appears to be a very small loss of kinetic energy of the tibia, as can be seen in figure 2. The reduction of kinetic energy of the tibia at the end of the swing phase is steeper in the perturbed step than in the normal one. From this graph it could be concluded that the perturbation does not cause large energy disturbance. Nevertheless, during the perturbation there is a large change in the kinetic energy of the trunk. The leg is braked at the end of the swing and this braking is quickly transmitted to the trunk. So, the major effect of the perturbation is the large loss in the trunk speed.

There are large differences found in the trunk energy during the following right step. Essentially the recovery consist of a quick step to recover from the speed loss.

Discussion

In order to avoid a fall, the subject has to compensate the perturbing energy in an efficient way by adjusting the joint powers, i.e. generating or dissipating energy.

In the early swing perturbation, the disturbed (left) step shows a large peak in the kinetic energy of the tibia, after the perturbation stops, in order to compensate as much as possible the blocking of the swing. This is coherent with the mechanism of an elevating strategy, where the swinging limb is brought forward and elevated to cross the perturbation. Also, the trunk energy suffers some changes, mainly after the

perturbation has stopped, these adjustments are due to the changes in step time and length. The important aspect concerning the limitations is to calculate the required joint powers to perform this action. In the late swing disturbance, it is interesting to see how the trunk energy is immediately changed when the perturbation appears. It seems reasonable that, as the swinging limb is about to contact the ground to accept the weight of the trunk, and, unlike the early swing perturbation, there is no time available for compensations during the swing, the trunk has to be quickly braked and the swinging limb brought to the ground.

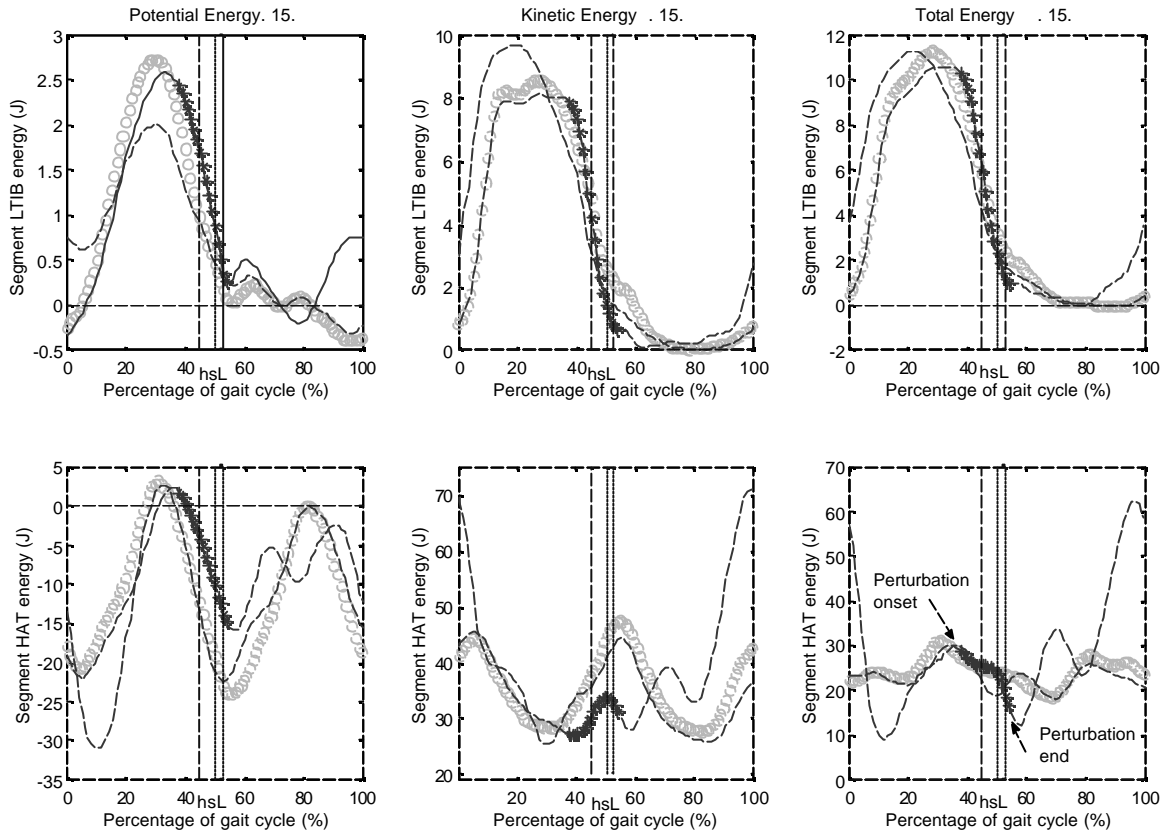


Figure 2: Potential, kinetic and total energies of the left (perturbed) tibia and trunk segments of a late swing perturbation with lowering strategy. Three strides: normal (circled grey), perturbed (solid thin line) and recovery (dashed line) are plotted with respect to the percentage of gait cycle (consecutive right heel strikes). The perturbation is shown by asterisks. Vertical lines indicate left heel strikes.

The recovery strategies impose requirements on the timing and magnitude of joint moments and power that the subject has to apply to avoid falling, that will reveal different types of limitations in the recovery. Limitations are in terms of maximal joint moment or power, while dealing with failure mechanisms as falling backwards or forwards, scuffing the ground at mid-swing, or in case of treadmill walking, keeping up the speed. If infinite joint power would be available, a very quick recovery would be hypothetically possible. This approach is very promising in the evaluation of the limits in which perturbation recovery is possible and the limitations that condition the response in frail populations like the elderly or pathological cases, especially when combined with models of human gait.

References

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