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Hitting a support surface at unexpected height during walking induces loading transients

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ABSTRACT

The impact phase during walking is sometimes characterised by an early loading peak, termed 'transient', followed by a brief decline in the force profile, termed 'unloading phase'. It was hypothesized that transients occur more frequently when subjects are unaware of the landing condition, and that the unloading phase represents a yield of the leg. This was tested experimentally by introducing an unexpectedly lowered or level support surface height during walking. Furthermore, associations between the unloading phase and type of foot placement, load-rate, kinesiology and centre of pressure were investigated.

The transient occurred more frequently when subjects were unaware of the surface height. The amplitude of unloading was higher in flatfooted (combined), as compared to heel and toe landings. The percentage of combined landings, as well as the amplitude and duration of unloading were highest in the first unexpected level trials (UL1) and gradually decreased in the subsequent level trials, when subjects adapted to the situation. Following the UL1 unloading phase, the foot roll-off was halted, the ipsilateral knee flexed, the onset of the contralateral swing phase was delayed, and the double support phase increased. The unloading amplitude correlated significantly with the load-rate and knee flexion.

It is concluded that an unexpected surface height frequently induces an early stance transient that is followed by an unloading phase, flexion response and halt in foot roll-off. These characteristics deserve further study in the context of the frequent falls induced by uneven surfaces during walking.

1. Introduction

Loading plays an important role in the regulation of gait [1]. At the moment of foot contact, the body mass has to be transferred smoothly in order to ensure stability and prevent injuries [1,2]. However, a smooth transition does not always occur. In the latter case, the force profile in the first 50 ms following landing is characterized by a peak, also termed 'transient' (see Fig. 1C). These transients have been described in walking [3–5], running [6–8] and landing from jumps [7–10]. The height of the transient depends on the amount of shock absorption at foot contact such as provided by footwear [3–5,7,8,10], the material of the landing surface [8,11,12] and the speed with which the foot hits the support surface [7,8,13–15]. An important element to manage the impact force is limb architecture. Flexing the knee reduces the rigidity of the leg and thereby facilitates shock absorption [2,8,9,13–18]. Furthermore, landing on the forefoot has been shown to reduce the transient by enabling energy absorption through eccentric contraction of the plantar flexor muscles [11,16,17]. The transient has also been associated with inappropriate muscle activity preceding foot contact, both during normal gait [5] and as a consequence of physical fatigue during running [6].

In addition, mental factors may attribute to the transient, in particular the awareness of the level of the support surface. The transient has previously been associated with delayed muscle activity after landing from an unexpected jump [19]. Therefore, it is hypothesized that the occurrence of a transient during gait may be facilitated by landing on an unexpected level of support, due to a mismatch between the produced and required muscle force at the moment of impact. Such conditions were recently imitated with subjects stepping on a surface that was either lower or higher than

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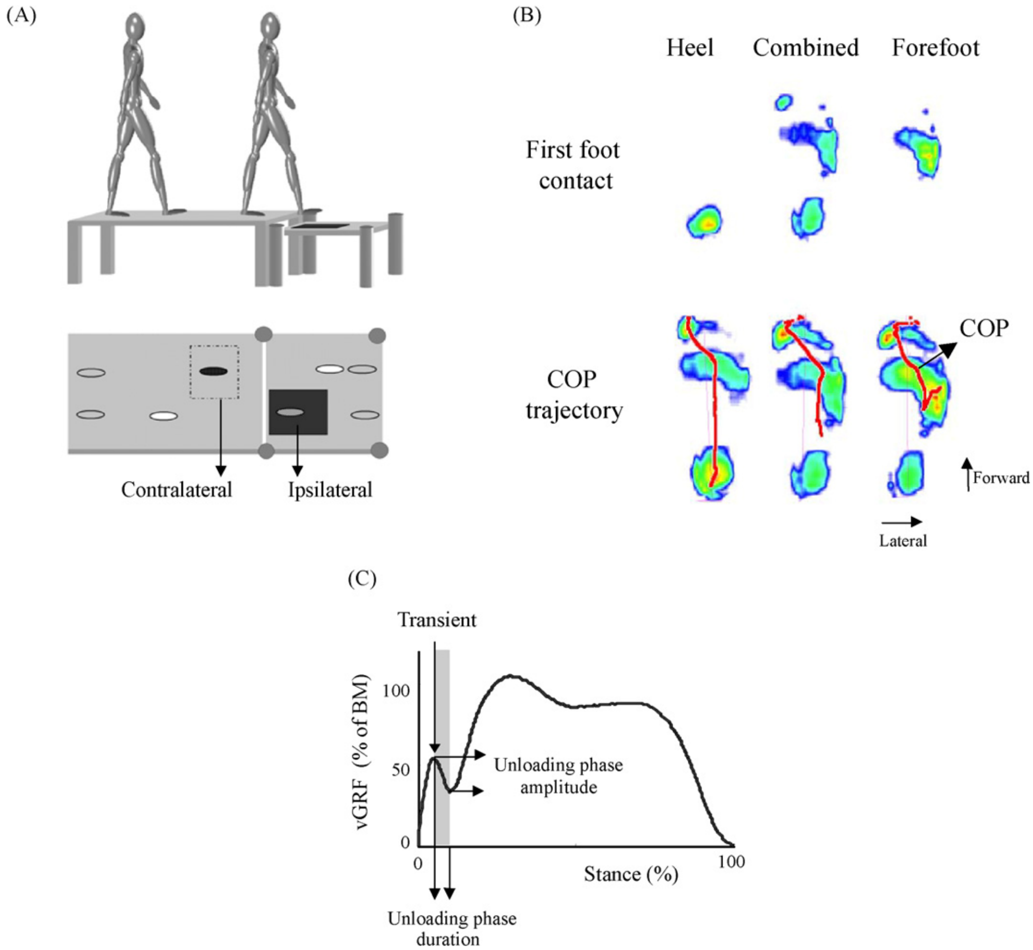

Fig. 1. Methods (A) Experimental set-up, consisting of a 2.6 m long walkway which ended on a gravity driven platform of 1 m^2 that could unexpectedly lower the ground support surface before the onset of a perturbed trial by 5.0 cm. (B) Foot landing strategies; the top illustrates the first foot contact of the heel, combined and forefoot landing. The bottom illustrates the total foot contact profile and centre of pressure (COP) trajectory of the foot. COP trajectories were analyzed in a foot reference space. The *y*-axis was placed over the medial part of the heel and the head of the second metacarpal bone, such that the *y*-axis was in the forward direction of foot roll-off. The *x*-axis (lateral direction) was perpendicular to the *y*-axis and placed at the posterior edge of the heel. (C) Vertical ground reaction force profile (vGRF) illustrating the transient and amplitude and duration of the unloading phase (shaded area). The unloading phase was defined as the period from the start of the decline till the onset of the ensuing incline in the vGRF curve.

expected [20]. It was found that the muscle activity preceding foot contact indeed differed from trials with an expected moment of landing. In addition, the unexpected landing induced changes in foot placement and speed of loading. Therefore, type of foot placement and speed of loading are possibly associated with the transient as well.

The transient is followed by a brief decline in the force profile, termed 'unloading phase' (Fig. 1C). Unloading phase characteristics have not received much scientific attention thus far. In accordance with hopping experiments on an unexpectedly stiff surface, which has shown a yield of the leg [23], we hypothesize that the unloading phase is a reflection of a temporary giving way of the leg, possibly associated with a loss of stability. Such a temporary loss of balance may lead to the recurrent outdoor falls in elderly subjects [21] and in neuropathy patients [22] that have been observed due to stepping on uneven surfaces. Since the unloading phase has not been studied thus far, this paper focussed on a homogeneous sample of healthy young adults.

In summary, the awareness of the level of support has hardly been studied with respect to the transient, neither have the biomechanic consequences. Therefore, we studied the prevalence of the transient following an unexpected support surface height during walking, and secondly, possible determinants for the amplitude and length of the unloading phase, such as type of foot placement, level of unexpectedness and initial load-rate. Thirdly, we investigated associated changes in the centre of pressure trajectory and lower limb kinesiology.

2. Methods

2.1. Subjects

Twelve young adults (5 male) participated (mean ± S.D.; age 24 ± 3 years, height 1.76 ± 0.12 m, body mass 67 ± 13 kg). None of the subjects had a neurological or musculoskeletal disease. The experiment was approved by the regional ethics committee. All subjects gave their informed consent.

2.2. Experimental set-up and instrumentation

Subjects walked on a walkway that ended on a gravity driven platform of 1 m^2 that could be unexpectedly lowered by 5.0 cm (Fig. 1A) [24]. Step cadence was successfully standardized by the use of a metronome, set at 1.5 Hz. Subjects wore glasses that blocked the lower part of their visual field to deprive them from visual information about the condition of the ground surface. The partial visual occlusion forced subjects to walk more cautiously (increased double support phase duration, reduced push-off force).

To control head position, subjects were instructed to look at a marker on a wall straight ahead. In between the trials, distracting noise of falling platforms was played over earphones, to prevent the subjects from hearing the lowering of the platform. The gravity driven platform embedded a footscan pressure plate (RsScan International®, Olen, Belgium, 500 Hz) to determine the area of first foot contact, the location of the centre of pressure (COP, Fig. 1B) and the vertical ground reaction force (vGRF, Fig. 1C). All subjects wore appropriately sized gymnastic shoes with