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Postural stability when walking: Effect of the frequency and magnitude of lateral oscillatory motion

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ABSTRACT

While walking on an instrumented treadmill, 20 subjects were perturbed by lateral sinusoidal oscillations representative of those encountered in transport: frequencies in the range 0.5–2 Hz and accelerations in the range 0.1–2.0 ms^{-2} r.m.s., corresponding to velocities in the range 0.032–0.16 ms^{-1} r.m.s. Postural stability was assessed from the self-reported probability of losing balance (i.e., perceived risk of falling) and the movements of the centre of pressure beneath the feet. With the same acceleration at all frequencies, the velocities and displacements of the oscillatory perturbations were greater with the lower frequency oscillations, and these caused greater postural instability. With the same velocity at all frequencies, postural instability was almost independent of the frequency of oscillation. Movements of the centre of pressure show that subjects attempted to compensate for the perturbations by increasing their step width and increasing their step rate.
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1. Introduction

Standing and walking require continuous postural control to counteract the destabilizing effects of gravity and self-induced movements of the body. Maintaining balance is more challenging when there are external disturbances from motion of the floor, such as when standing or walking in a moving train, bus, aircraft or ship.

Sudden accelerations or decelerations of a treadmill (Berger et al., 1984) or a moveable platform embedded in a walkway (e.g., Nashner, 1980; Oddsson et al., 2004; Bhatt et al., 2005) have been used to investigate responses to slips, trips, and missteps encountered during walking. Longer duration low frequency oscillations (0.2–0.5 Hz) of a treadmill on a six-axis motion platform (e.g., Brady et al., 2009; McAndrew et al., 2010) have been used to investigate postural responses to perturbations when walking but have not been representative of motions encountered in transport.

With instantaneous increases in horizontal acceleration, stationary standing people have been reported to tolerate accelerations up to 0.76 ms^{-2} in the backward direction, 0.48 ms^{-2} in the forward direction, and 0.33 ms^{-2} in a sideways direction (Jongkees and Groen, 1942 – as cited by De Graaf and Van Weperen, (1997)). Similar thresholds were obtained by De Graaf and Van Weperen, (1997), who found that standing subjects were most sensitive to lateral acceleration when standing with their feet almost together. Postural stability when standing still and exposed to narrow-band random fore-and-aft and lateral oscillation has been studied at frequencies between 0.125 and 2.0 Hz with velocities from 0.04 to 0.16 ms^{-1} r.m.s. (Nawayseh and Griffin, 2006). The displacement of the centre of pressure (COP) and subject estimates of the probability of losing balance increased with increasing magnitude of oscillation and, with the same velocity at all frequencies, stability problems were greatest around 0.5 Hz. Tolerances of walking subjects to sideward oscillations in transport have not been previously reported.

Understanding of the physiological and biomechanical aspects of balance has been used to develop active models of postural stability when standing (e.g. Mergner et al., 2006; Peterka, 2003). These models represent the neural, sensory, and biomechanical subsystems involved in human postural control but do not allow the prediction of the probability of falling. People may be expected to be more stable when standing and supported on two legs than when walking and supported on only one leg for 80% of the gait cycle (Woollacott and Tang, 1997), especially when threatened by external perturbations.

The main strategy used to maintain balance during locomotion is the stepping strategy (Nashner, 1980; Horak and Nashner, 1986; Hof et al., 2007). Additional strategies (e.g. active hip torque and active ankle subtalar torque) are used for fine tuning (Hof et al., 2007; MacKinnon and Winter, 1993) when the foot position is established. Adjusting the step width by varying the foot placement

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maintains postural stability in the frontal (i.e., coronal) plane by regulating the trajectory of the centre of mass (COM) (Townsend, 1985) and has a greater influence on postural control during unperturbed walking than either step length or step time (Owings and Grabiner, 2004). It has been suggested that step width is adjusted to compensate for lateral acceleration induced by external perturbation (Oddsson et al., 2004).

The overall aim of the study reported in this paper was to determine how postural stability when walking is influenced by the magnitude and the frequency of lateral oscillation of the floor. It was hypothesised that, at each frequency of oscillation, the self-reported probability of losing balance and the movement of the centre of pressure in the lateral direction would increase with increasing magnitude of oscillation. It was expected that the movement of the centre of pressure would vary with the frequency of oscillation in a manner that would explain the frequency-dependence of the loss of balance.

2. Method

2.1. Subjects

Twenty healthy male subjects median age 27 years (range 25–41), stature 177 cm (range 165–192), weight 72.3 kg (48.5 kg–88.45) participated in the study. Subjects completed a questionnaire to exclude those with relevant disorders or using drugs that might affect postural stability. Informed consent was obtained prior to participation in the experiment that was approved by the Human Experimentation Safety and Ethics Committee of the Institute of Sound and Vibration Research.

2.2. Apparatus

A treadmill (Kistler Gaitway®) incorporating eight force sensors was used to provide the walking task and measure the vertical ground reaction forces during walking. Subjects were secured by a safety harness connected via two loose straps to a frame around the treadmill (Fig. 1). The harness allowed subjects to move freely in the plane of progression but prevented their knees or hips contacting the floor if they fell. A safety net was positioned behind the subjects as a precaution in case they slid backwards while walking on the treadmill.

Lateral oscillatory motion was generated by a six-axis motion simulator in the Human Factors Research Unit at the Institute of Sound and Vibration Research. The simulator is able to provide translational displacements of ± 0.5 m in the lateral direction at accelerations up to about ± 10 ms^{-2}.

Acceleration in the lateral direction was recorded by accelerometers on the simulator platform (FGP model FA101-A2-5G). Data acquisition via the treadmill software was triggered at the moment the 4½-cycle acceleration commenced. The acceleration and force data collected by the Gaitway® data acquisition system were sampled at 100 samples per second and stored in a personal computer.

2.3. Experimental procedure

While walking on the treadmill, subjects were perturbed by simple transient lateral acceleration stimuli applied at an unpredictable time. The stimuli were 4.5 cycles of sinusoidal motion modulated by a half sine envelope. For these waveforms, the peak acceleration and the peak velocity are, respectively, double the r.m.s. acceleration and r.m.s. velocity. The motions start and end with zero displacement, velocity and acceleration and were chosen as being broadly representative of lateral motions experienced in trains (Fig. 2a).

At each of seven frequencies (0.5, 0.63, 0.8, 1.0, 1.25, 1.6, 2.0 Hz), the motions were presented at eight velocities (0.032, 0.04, 0.05, 0.062, 0.08, 0.1, 0.125, 0.16 ms^{-1} r.m.s.). This resulted in accelerations in the range 0.1–2.0 ms^{-2} r.m.s. (Fig. 2b). The frequencies and magnitudes were chosen after preliminary experimentation and so that the effects of stimuli with the same magnitude of acceleration or stimuli with the same magnitude of velocity could be compared across the frequency range. The 56 motions were presented in a random order.

The speed of the treadmill was selected so that subjects walked at 0.7 ms^{-1} throughout the experiment. This was the preferred comfortable walking speed of subjects who participated in preliminary experiments.

The eight channels of force data were acquired throughout each of the 4½-cycle perturbations. After experiencing each motion, subjects were asked to judge their postural stability by answering the following question:

"What is the probability that you would lose balance if the same exposure were repeated?"

Subjects were instructed to fix their vision on the board in front of them (which moved with the lateral motion of the simulator) and to grasp the handrails of the treadmill only if it was really

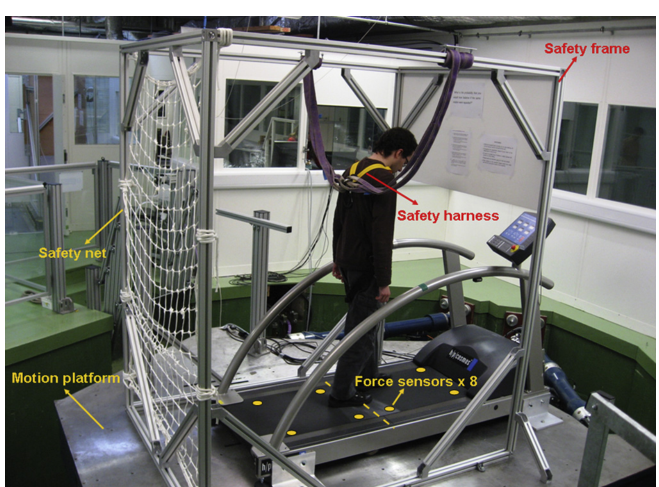

Fig. 1. Experimental apparatus.

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