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Full Length Article

Responses of human ankle muscles to mediolateral balance perturbations during walking

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ABSTRACT

During walking our balance is maintained by muscle action. In part these muscle actions automatically respond to the imbalance. This paper considers responses to balance perturbations in muscles around the ankle, peroneus longus (PL), tibialis anterior (TA) and soleus (SO). It is investigated if their action is related to previously observed balance mechanisms: the 'braking reaction' and the mediolateral ankle strategy.

Subjects walked on a treadmill and received pushes to the left and pulls to the right in various phases of the gait cycle. Muscle actions were divided into medium latency R1 (100–150 ms), long latency R2 (170–250 ms), and late action R3 (270–350 ms). Short latency responses, before 100 ms, were not observed but later responses were prominent. With inward perturbations (e.g. pushes to the left shortly before or during stance of the right foot) responses in RPL were seen. The forward roll-over of the CoP was briefly stalled in mid stance, so that the heel was not lifted. Stance was shortened. With outward perturbations, pushes to the left shortly before or during stance of the left foot, responses in all three muscles, LTA, LSO, and LPL were seen. Our interpretation is that these muscle activations induce a 'braking reaction' but could also contribute to the 'mediolateral ankle strategy'. The resultant balance correction is small but fast, and so diminishes the need for later corrections by the stepping strategy.

1. Introduction

In human walking forward movement is the main aim. Lateral movements are much smaller and more irregular. It has been shown by several investigators, however, that they are essential for mediolateral balance. The most obvious of the movements that ensure mediolateral balance is foot placement (Bauby & Kuo, 2000; Hof, Vermerris, & Gjaltema, 2010; Townsend, 1985). After a perturbation to the right or left, in the next step the foot is placed more to the right/left than usual, away from the perturbing force. As a result the subject 'falls' in the opposite direction and, when the side step is of the correct magnitude, balance is restored. In a previous paper we have reported that increased leg abduction movements in response to lateral perturbations can be linked to reflexes of hip abductor gluteus medius, i.e. stereotyped bursts in the electromyogram (EMG) with a fixed latency (Hof & Duysens, 2013). In cats similar effects have been observed (Misiaszek, 2006; Karayannidou et al., 2009).

The primary purpose of the research presented here is to investigate if similar muscle activations can be found in muscles around the ankle, in particular in mm. soleus, tibialis anterior and peroneus. The second purpose is to see if these activations can be linked to balance mechanisms. A first balance mechanism, the 'braking reaction', is that forward movement stalls and stance duration is

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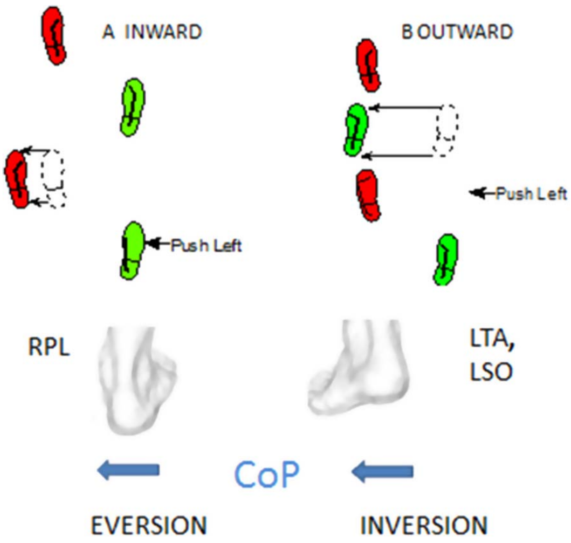

Fig. 1. Schematic diagram of the balance reactions after a push from the left. A. After an *inward* push, e.g. a leftward push during right stance, the course of the center of pressure (CoP) during right stance is displaced medially (thick line under right footsole). This means an eversion of the right foot, produced by right peroneus longus. B. After an *outward* push, e.g. a leftward push during left stance, the course of the CoP during left stance is displaced laterally. This means an inversion of the left foot, produced by left tibialis posterior and anterior. These effects during the ongoing stance phase are known as the 'mediolateral ankle strategy'. Following this action, in the next stance phase the contralateral foot is positioned more to the left, the 'stepping strategy'.

shortened (see Fig. 2C in Hof et al. (2010)). The balance correction in the next step can then be applied earlier and instability has less time to develop. The basis for stance shortening is unknown but it is hypothesized that some type of brief freezing could be involved as shown in other perturbation studies (Nakazawa, Kawashima, Akai, & Yano, 2004; Potocanac, Pijnappels, Verschueren, Dieën, & Duysens, 2015). Hence the expectation here is that the perturbation could lead to co-contraction of several muscles around the ankle, leading to an interruption of forward progression and shortening of the stance phase.

A second balance mechanism to be investigated is known as the 'mediolateral ankle balance strategy' (Hof et al., 2010). This strategy concerns the foot roll-over. In plantigrade animals like humans, the foot sole has an appreciable area, over which the pressure to the ground is distributed. As a result, the center of pressure (CoP) of the ground reaction force can move over a considerable area (Hof, Gazendam, & Sinke, 2005). This is already evident in unperturbed walking. At foot contact the CoP is in the heel region. In the course of stance it 'rolls over', first forward and somewhat laterally, then medially and forward to the big toe. We have already shown (Hof et al., 2010) that this roll-over is modified in response to a perturbation; the CoP moves always away from the push. In case of an inward (medially directed) perturbation the CoP is thus displaced medially. (Fig. 1A) and in case of an outward (laterally directed) perturbation the CoP shift is lateral, Fig. 1B. The magnitude of this medio-lateral CoP shift is not great, one or two cm to the left or right, but it can be applied much faster than the stepping strategy which becomes only effective at the placement of the contralateral step. In the unstable situation of walking, an early small correction reduces the need for a large late correction.

Movement of the CoP over the footsole is caused by muscle action. The muscles at the ankle cross both the tibiotalar joint, which permits plantar- and dorsiflexion, and the subtalar joint, which permits in- and eversion (Inman, Ralston, & Todd, 1981). The position of the CoP under the foot in standing that results from muscle forces depends on the course of the muscle tendons with respect to both these joints (Kim, Uchiyama, Kitaoka, & An, 2003). In our experiments surface electromyograms (EMGs) were recorded bilaterally from peroneus longus (PL), which gives eversion and plantarflexion, tibialis anterior (TA), giving dorsiflexion and inversion, and soleus (SO), giving plantarflexion and some inversion (Fig. 2). Inversion and eversion give rise to lateral and medial displacement of the CoP, respectively (Kim et al., 2003). No recordings could be made of tibialis posterior (TP), a major invertor. This deep lying muscle is not accessible by surface EMG and intramuscular needle or fine-wire EMG was not attempted in our experiments for ethical reasons. For this reason only TA was available as a representative of the invertors.

In the experimental set-up the subject walks on a treadmill which records continuously the location of the CoP. The perturbations are short (100 ms) pushes (to the left) or pulls (to the right) applied to the trunk by means of a pneumatic device. The perturbations are timed at all phases of the walking cycle (see Methods). EMGs are recorded bilaterally by surface EMG. This research is aimed at detecting reflexes: EMG responses of a well-defined duration above the usual unperturbed walking activity ('background') at a well-defined delay after the perturbation.

In the case that CoP movements are indeed (at least partly) related to muscle activations, one expects EMG responses to lead and partially overlap the CoP motions. After an inward perturbation, action of ipsilateral PL is expected, to move the CoP medially.

In contrast, when a push is applied outward, action of contralateral TA is primarily expected. This moves the CoP laterally.

Since the perturbations were unexpected, one may expect some type of minor "startle" to occur as well. Such reactions are characterized by a brief 'brake', related to a co-contraction of antagonist muscles, as seen in other unexpected perturbations during gait (Nakazawa et al., 2004; Nieuwenhuijzen, Schillings, Galen, & Duysens, 2000).