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Effect of active arm swing to local dynamic stability during walking

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ABSTRACT

Arm swing is an essential component in regulating dynamic stability of the whole body during walking, while the contribution of active arm swing to local dynamic stability of different motion segments remains unclear.

This study investigated the effects of arm swing under natural arm swing condition and active arm swing condition on local dynamic stability and gait variability of the trunk segments (C7 and T10 joint) and lower extremity joints (hip, knee and ankle joint). The local divergence exponents (λ_s) and mean standard deviation over strides (MeanSD) of 24 young healthy adults were calculated while they were walking on treadmill with two arm swing conditions at their preferred walking speed (PWS).

We found that in medial–lateral direction, both λ_s and MeanSD values of the trunk segments (C7 and T10 joint) in active arm swing condition were significantly lower than those in natural arm swing condition ($p < 0.05$), while no significant difference of λ_s or MeanSD in lower extremity joints (hip, knee and ankle joint) was found between two arm swing conditions ($p > 0.05$, respectively). In anterior–posterior and vertical direction, neither λ_s nor MeanSD values of all body segments showed significant difference between two arm swing conditions ($p > 0.05$, respectively).

These findings indicate that active arm swing may help to improve the local dynamic stability of the trunk segments in medial–lateral direction.

1. Introduction

The reduction and loss of balance control during walking may lead to falls (Overstall, Exton-Smith, Imms, & Johnson, 1977; Winter, 1995), which is a major factor that causes the death and injury of the elderly (Gillespie et al., 2009; Wang, Chen, & Song, 2010). Human dynamic stability during walking has been considered as an important index to evaluate the

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fall risk (Bruijn, Meijer, Beek, & Van Dieën, 2013). It is defined as the ability to maintain locomotion balance measured by the body sensitivity to perturbations during walking. Internal perturbations, like neuro-control errors, exist during a steady-state gait. The ability of maintaining balance to response such perturbations is called local dynamic stability. The ability of balance regaining and recovery from an outside perturbation, like a slip or trip, is called global dynamic stability (Bruijn, Bregman, Meijer, Beek, & van Dieën, 2012; Bruijn et al., 2013).

Arm swing was thought as an essential component to adjust walking balance during human walking (Pijnappels, Kingma, Wezenberg, Reurink, & van Dieën, 2010; Roos, McGuigan, Kerwin, & Trewartha, 2008). The active response of driving the arm muscle to emphasize upper limb during walking was reported to have a positive role in the global dynamic stability. Pijnappels' study found that (Pijnappels et al., 2010), active arm swing would help the body regain balance after outside perturbation, by postponing the transfer of arm angular momentum to the trunk. As for the steady-state gait, Nakakubo et al. recently found that a deliberately emphasized arm swing during gait may improve the trunk stability of old adults in the medial–lateral direction (Nakakubo et al., 2014); Punt et al. found that at all walking speed, dynamic stability in medial–lateral direction was improved with excessive arm swing. At low walking speed, stability in anterior–posterior and vertical direction would also be improved by swinging arm excessively (Punt, Bruijn, Wittink, & van Dieen, 2015). However, these two studies regarded the whole body as a single unit, and only focused on the gait stability of the trunk segment, while neglecting the evaluation on the lower limb joints. Lower limb joints are major segments that drive the gait motion and keep walking balance. Therefore, the effects of active arm swing on local dynamic stability of different motion segments, including trunk segments and the lower extremity joints need to be further studied.

The local divergence exponent is a measure of local dynamic stability based on the non-linear dynamic theory. Directly quantifying the resistance of the neuromuscular system to infinitesimally small perturbations, the local divergence exponents (λ_{max}, i.e. the maximum finite-time Lyapunov exponents) estimated from human walking kinematics mainly focused on the locomotion control of dynamic stability during continuous walking (Bruijn et al., 2013; Dingwell & Cusumano, 2000). This measure characterized how fast the neighboring trajectories of a reconstructed state space (e.g. displacement, velocity, acceleration) diverge after a small perturbation (Bruijn et al., 2013; Dingwell & Cusumano, 2000). The larger the local divergence exponents are corresponded to a poorer ability of balance recovery (i.e. less stable gait). Recent studies found that the local divergence exponent calculated from short-term strides (often 1 stride cycle, labeled λ_s) could be used to forecast the probability of falling during human walking (Bruijn et al., 2012; Roos et al., 2008). Additionally, the validity of λ_s was proved to be best supported in falling prediction across many levels compared with other measures, including construct validity, predictive validity in models, convergent validity in experimental studies, and predictive validity in observational studies (Bruijn et al., 2013).

Therefore, the objective of this study was to investigate the effects of natural arm swing and active arm swing on local dynamic stability of the trunk segments and lower extremity joints during walking, by calculating their short-term local divergence exponents (λ_s). The mean standard deviation (MeanSD) was further quantified as the amount of gait variability to provide more insight into the difference between two arm swing conditions. Since Roos et al. found that explicitly controlling arm swing may reduce the neuromuscular noise, thus resulting in lower λ_s (Roos et al., 2008), we hypothesized that under active arm swing condition, the dynamic stability of the trunk and lower extremity joints would be improved, and the variability would be decreased.

2. Materials and methods

2.1. Participants

Twenty-four young (10 women, 14 men; age 24.94 ± 1.43 years; height 1.704 ± 0.083 m, BMI 20.62 ± 2.52 kg/m^2) healthy volunteers participated in the study. Informed consent was reviewed by the Institutional Review Board (IRB) at Biomedical Engineering School of Shanghai Jiao Tong University and obtained from each participant prior to data collection. None of the volunteers had orthopedic or neurological disorders.

2.2. Experimental procedures

For familiarization, each participant was instructed to walk on a level treadmill (F80 Sole Fitness, Jonesboro, AR, USA, with the deck size of 94 cm × 210 cm and running surface size of 56 cm × 152 cm) for 10 min under two arm swing conditions: with natural arm swing (NAS, arms swing in a relaxed manner to avoid tensing shoulder or arm muscles) and with active arm swing (AAS, voluntary arms swing actively driven by shoulder or arm muscles). During the experiment, subjects were asked not to hold or touch the treadmill handles by hands or by other body parts. To protect the subjects from accidental tripping or falling, they were wearing a safety harness settled at their waists when walking on the treadmill. The preferred walking speeds (PWSs) of each subject during each arm swing condition was determined and recorded using a previously published protocol (Roos et al., 2008). The participants then rested at least 2 min before the data collection began.

For the experimental trials, participants completed one 5-min walking trial under each arm swing condition at their PWS with at least 5-min rest between trials. The order of the two trials was randomized. The kinematics of trunk (7th cervical vertebra (C7) and 10th thoracic vertebra (T10)) and three lower extremity joints (hip, knee and ankle) were recorded at a