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Full Length Article

Adaptation of kinematic synergy and postural control to mechanical ankle constraint on an unsteady stance surface

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ABSTRACT

Joint constraint interferes with the coordinative structure in joint movements used to optimize postural stability. This study aimed to investigate changes in postural synergy when the ankle joints were bilaterally braced during a stabilometer stance. Twenty-four young adults stood on a stabilometer plate while wearing a pair of ankle–foot orthoses, which were either unlocked or locked to restrict ankle motion (the ankle constraint (AC) and non-constraint (NC) conditions). Although ankle constraint did not significantly affect the dynamics of the stabilometer movements, the size and regularity of the first principal component (PC1), which explained more than 80% of the variance of joint movements in the lower limb, were increased. In addition, PC1 exhibited higher communalities with angular movements of the knee and hip joints in the AC condition than in the NC condition. Those subjects who exhibited a constraint-induced increase in postural sway (the I group) showed greater increases in the size and regularity of PC1 than did those who exhibited reduced postural sway during ankle constraint (the D group). Constraint-induced changes in postural synergy were group-dependent. Only the I group exhibited an increase of communality of PC1 with the hip angular movement following bilateral ankle constraint. In summary, bilateral ankle constraint altered the coordination solution, with increasing reliance on compensatory knee movement to maintain a balanced posture on the stabilometer. However, accessory hip movement due to ankle constraint was not economical and was disadvantageous to stance stability.

1. Introduction

Kinematic motor abundance, refined from the idea of motor redundancy (Bernstein, 1967), refers to the ability of the brain to facilitate a small repertoire of patterned motions across the joints (or coordination solutions) to accomplish task goals in a flexible manner (Latash, 2012; Yang, Scholz, & Latash, 2007). The regulation of the degrees of freedom is tuned to the nature of the task and the environmental context (Oytam, Neilson, & O'Dwyer, 2005). With skill advancement, the selection of coordination solutions often conforms to the economical principle so that humans can minimize kinematic redundancy to achieve task goals by making use of the mechanical advantage of muscles. For instance, unlike a non-dancer, a ballet dancer can maintain a quiet posture while standing *en pointe* with a decrease in the mechanical degrees of freedom (Tanabe, Fujii, & Kouzaki, 2014).

According to the model of a single inverted pendulum (Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998), quiet standing is achieved through a combination of active and passive mechanisms of the ankle joint, including neural control and the viscoelastic

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properties of the calf muscle (Sasagawa, Shinya, & Nakazawa, 2014; Sakanaka, Lakie, & Reynolds, 2016). Although the ankle joint is considered critical to maintaining upright bipedal equilibrium, the inverted pendulum model could be oversimplified, for earlier studies have emphasized the roles of the knee and hip joints in postural corrections (Gunther, Grimmer, Siebert, & Blickhan, 2009; Gunther, Putsche, Leistritz, & Grimmer, 2011). When the ankle joint is constrained, such as when an ankle brace, ski boots, or a prosthetic foot with a limited range of motion is worn, stance stability is expected to be altered due to the resultant limited effective range of motion (Jeon, Hwang, & Woo, 2013), decline in proprioception (Tchorzewski, Bujas, & Jankowicz-Szymanska, 2013), and changes in the appropriate mechanical states of the local joint and other joints in the kinematic chain (Gunther & Wagner, 2016). By recruiting different biomechanical degrees of freedom to the postural system (Guo, Yang, Huang, & Hwang, 2012; Hodges, Hayes, Horn, & Williams, 2005), compensatory actions of the knee and hip joints are called into play to minimize stance destabilization and joint stress in the lower limb in case of relatively high segment velocities and accelerations (Cheng & Yeh, 2015). Surprisingly, mechanical constraint of the ankle joint does not necessarily lead to the degradation of stance steadiness on a level surface (Jeon et al., 2013).

A stabilometer stance, which addresses foot-support interaction, is commonly used to assess dynamic standing-balance ability in rehabilitation clinics. It provides a scalable balance constraint with a specific focus on ankle torque to cope with body shifts (Ivanenko, Levik, Talis, & Gurfinkel, 1997). The difficulty of the stabilometer stance and participation of the ankle joint in maintaining balance depend on the radius of curvature and the height of the stabilometer (Almeida, Carvalho, & Talis, 2006; Bernstein, 1967; Cimadoro, Paizis, Alberti, & Babault, 2013; Noe, Garcia-Masso, & Paillard, 2017). When the ankle joint is braced, an adaptive strategy should be developed to meet the particular task demand and stance configuration (Kilby, Molenaar, & Newell, 2015). Nevertheless, the adaptive strategies selected to cope with ankle constraint could vary with individuals, depending on their motor expertise. Therefore, this study aimed to investigate hidden facets of postural synergy during a stabilometer stance under the condition of ankle constraint. We hypothesized that 1) ankle constraint would lead to structural changes in posture dynamics and inferior postural stability during the stabilometer stance, 2) ankle constraint would alter the relative significances of joint contributions in the lower limb to the stabilometer stance, and 3) constraint-induced change in stance stability would be dependent on how the coordination solution was reorganized.

2. Methods

2.1. Participants

A total of 24 young healthy participants (12 males, 12 females; mean age: 25.2 ± 4.6 years old; height: 166.63 ± 8.28 cm; weight: 62.67 ± 15.70 kg) from the university campus participated in this study. They had neither neuromuscular disorders nor any history of surgery on the lower limbs. The participants provided written informed consent approved by the Human Research Ethics Committee of the National Chung Kung University Hospital (NO. B-ER-105-062).

2.2. Experimental procedures

All participants wore a pair of custom-made ankle–foot orthoses and were instructed to maintain an upright stance on a stabilometer (a wooden platform (50 cm × 58 cm) with a consistent curved base (radius: 25 cm; height: 25 cm). There were also instructed to stand with both arms naturally hanging at their sides and to maintain the stance as steadily as possible in the non-constraint (NC) and ankle constraint (AC) conditions. In the NC condition, the joints of the adjustable, simple-hinged ankle–foot orthoses were unlocked so that the participants could make use of ankle dominant movements during the stance. In the AC condition, the ankle joints of the ankle–foot orthoses were locked in place with a pair of fixation screws. Both ankle joints were confined to the neutral position (ankle dorsiflexion of 90 degrees), although a ± 2 degree range of voluntary ankle motion was still possible in the AC condition. However, the constraint of ankle movement was adequate to cause compensatory movements during the stabilometer stance. The duration of each trial was 30 s, and four trials were collected for both the NC and AC conditions for all participants. The order of AC and NC trials was randomized across the subjects.

2.3. Devices and experimental setting

During the stabilometer stance in the NC and AC conditions, the stabilometer tilting angles and the joint movements of the ankle, knee, and hip joints were recorded with an inclinometer and electrogoniometers, respectively (Fig. 1). The inclinometer (Model FAS-A, LORD MicroStrain, USA) was mounted on the center of the stabilometer to register angular movements of the stabilometer plate. In accordance with the user's manual provided by the manufacturer, all the electrogoniometers (Model SG110/A and SG150, Biometrics Ltd, UK) were attached to the joint axes of the dominant lower limb, defined as the preferred leg for kicking a ball, to record the angular motions (flexion/extension and dorsiflexion/plantarflexion) in the sagittal plane. It was assumed that the angular movements of the dominant limb would be sufficient to account for the fluctuating movements of the stabilometer (Almeida et al., 2006). All participants were requested to wear loose shorts during the experiment. All sensors were attached on the subjects' skin with double-sided adhesive tape and then tightly wrapped with surgical tape and elastic bands to minimize potential movement artifacts. The ankle braces were positioned outside the ankle electrogoniometer, with the joint axis of the brace central to the lateral malleolus. For the ankle movement, distal and proximal sensors were placed along the distal lateral aspect of the lower leg just below and above the lateral malleolus, respectively. The distal and proximal sensors for the knee electrogoniometer were attached over the proximal