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Reduced plantar sole sensitivity induces balance control modifications to compensate ankle tendon vibration and vision deprivation

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ABSTRACT

The aim of this study was to investigate if sensory reweighting occurred to control balance when the sensitivity of the plantar sole is reduced using cooling. To address this question, visual information was manipulated and/or ankle proprioception was altered by Achilles tendon vibration. It was expected that Achilles tendon vibration and vision deprivation would induce greater center of pressure (CoP) excursions and/or increase of electromyographic (EMG) activity of the ankle muscles (triceps surea and tibialis anterior) with than without cooling of the plantar sole. To verify these hypotheses, the CoP and EMG activity of the ankle muscles were simultaneously recorded during quiet standing trials of 30s before and after feet cooling procedure. Results showed that plantar sole sensitivity alteration did not lead to larger CoP excursions even during Achilles tendon vibration in absence of vision. This could be explained by an increase in the EMG activity of the triceps surae after the cooling procedure without modification of tibialis anterior EMG activity. This study suggests that to compensate alteration in plantar sole sensitivity, the central nervous system increased the muscular activity of the triceps surae to limit CoP excursions.

1. Introduction

The central nervous system (CNS) integrates different sensory inputs such as the visual (Paulus et al., 1984), vestibular (Cathers et al., 2005; Horak et al., 1994), plantar sole mechanoreceptor (Kavounoudias et al., 1999, 2001) and proprioceptive (van Deursen and Simoneau, 1999) in order to control upright balance. When one (or more) of these sensory systems is altered, the CNS regulates balance by attributing a larger weight to the remaining afferent information, this is known as sensory reweighting (Peterka, 2002). Information from the sensory systems is naturally altered through the aging process, by pathologies, or can also be artificially altered. For instance, cooling the feet in a bath of iced water has been used to attenuate the sensitivity of the plantar sole (Billot et al., 2013; Eils et al., 2004, 2002; McKeon and Hertel, 2007; Patel et al., 2011; Perry et al., 2000; Schlee et al., 2009; Stal et al., 2003). Recently, our research group demonstrated that twelve minutes of plantar sole cooling induced a transitory alteration of balance control (Billot et al., 2013). In this experiment, after cooling, there was an increase in the center of pressure (CoP) speed for the first trial only. As well, there was a significant increase in electromyographic (EMG) activity for ankle muscles on the second and the third trials, suggesting an increase in ankle joint stiffness. However, from the fourth to the seventh trials, there was no apparent increase in either CoP speed or EMG activity despite maintaining decreased plantar sole tactile sensitivity. To compensate for the attenuated plantar sole sensitivity, it was suggested that the CNS performs sensory reweighting by increasing the weight of other available sensory information (i.e., visual and/or proprioceptive). Hence, it is hypothesized that a greater use of proprioceptive and/or visual systems are responsible for the return to normal balance control observed in our previous study. Therefore, it is likely that after the cooling procedure, a greater alteration of balance control should be observed if either vision is removed or ankle joint proprioceptive information is altered. To verify this hypothesis, CoP displacements were recorded before and after cooling the feet soles with and without Achilles tendon vibration while vision was available or not. Achilles tendon vibration was chosen as it simulates a stretch of the gastrocnemius muscles thus creating an illusion of a forward body tilt. To compensate for this illusion, a backward falling response is evoked (Eklund, 1972; Lackner,

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1988; Martin et al., 1980; Massion, 1992). It is hypothesized that attenuating the plantar sole sensitivity implies that a greater relative sensory weight should be attributed to ankle joint proprioception as this information is more reliable (sensory reweighting hypothesis). Consequently, for a similar vibration of the Achilles tendon, one would expect increased backward body sway with plantar sole sensitivity attenuated compared to without plantar sole sensitivity attenuation. It is also possible that the backward body sway could challenge balance stability resulting in the adoption of a stiffness strategy for balance maintenance. As a result, the EMG activity of the ankle muscles (i.e., triceps surea and tibialis anterior) would increase to maintain balance (stiffness strategy). In the event of a stiffness strategy it is further expected that ankle muscle co-activation would be even larger when vision will be removed and Achilles tendons are vibrated.

2. Methods

2.1. Participants

Eleven healthy young male adults (age: 27.4 ± 5.7 years, height: 175.3 ± 6.1 cm, weight: 75.0 ± 7.3 kg) participated. They were screened and excluded from participation if any of the following conditions were self-reported: neurological or orthopaedic disorders, lower extremity injuries, medication use and visual impairments. All participants were briefed and provided with a written informed consent prior to experimental testing. This experiment was approved by the institutional ethics review board and is in accordance with the Declaration of Helsinki.

2.2. Experimental procedure

For each participant, all experimental conditions were performed in one experimental session lasting approximately 1 h. For each trial, subjects were instructed to stand as still as possible on a force platform for 30 s. Subjects' feet were oriented at a 15° angle (feet positions were marked) from the sagittal midline with their heels 5 cm apart and arms positioned freely along the sides of the body. Balance control was assessed in four experimental conditions that were randomly presented. For two conditions, participants stood upright with and without vision for 30 s. When vision was available, the participants were asked to fix a target located 2 m in front of them at gaze level. The other two conditions (with or without vision) included Achilles tendon vibration (both legs). Two custom made vibrators were made with unbalanced masses fixed at both extremities of a DC motor. Each motor was embedded in a plastic cylinder (10 cm long, 3 cm in diameter) and produced a mechanical oscillation of 3 mm amplitude at 100 Hz (Simoneau et al., 2006). The vibrators were held in place by means of adjustable rubber bands.

Each of the trials with vibration started with an initial pre-vibration period followed by a vibration period and a post-vibration period. Each of these three periods was of equal duration (10 s). Seven trials per condition were given for a total of 28 trials. This procedure was done before and after attenuating plantar sole sensitivity (cooling), for a total of 56 trials.

2.3. Tactile testing

Prior to cooling, plantar sole sensitivity was quantified using tactile discrimination (monofilament) and acuity discrimination at the first metatarsus via two-point aesthesiometer (described previously in Billot et al., 2013). The sole sensitivity test consisted of a perpendicular application of the monofilament to three plantar sole sites (first metatarsus, fifth metatarsus and heel). During application, the participants were asked if they perceived the pressure or did not. For the two-point discrimination test, the two prong tips of the aesthesiometer touched perpendicular to the test site simultaneously on the heel and the participant simply stated if the contact was perceived as a single point or two separate points.

2.4. Cooling procedure

Participants immersed their feet (ankle depth) into cold water (temperature 0–2 °C) for ten minutes. Tactile testing was then performed and feet were re-immersed in water for another two minutes before balance control was assessed. After the cooling procedure, eight trials were collected within a five minute time period before the feet were re-immersed in cold water (3 min) before continuing with eight more trials. This cycle (cooling-data acquisition) was repeated until all trials were completed. The temperature was assessed on the heel of the plantar sole with a thermistor thermometer (Cole-Parmer model 8402-00), before and after cooling procedure. To expedite the acquisition process after cooling, these measurements were taken only once. In a previous study we documented that the plantar sole temperature was maintained at approximately 14 °C after several 8-min cycles of data acquisition followed by re-cooling periods (2–3 min) (Billot et al., 2013).

2.5. Data analysis

Force platform signals (Fz: vertical force, Mx and My: moments around the x and y axes) were amplified (AMTI, model MSA-6) and sampled at 200 Hz (16-bit analog to digital conversion; Measurement Computing USB-1616HS-BNC, Norton, USA). All signals were filtered (Butterworth fourth-order, 7 Hz low-pass cut-off frequency with dual-pass to remove phase shift) prior to computing CoP speed, antero-posterior (AP) and medio-lateral (ML) ranges, and RMS values for the CoP speed along both axes (RMSv AP and ML). The speed of the CoP corresponds to the cumulative distance over the sampling period. The range of the CoP displacement indicates the average minimal and maximal excursion of the CoP from the base of support. RMSv is analogous to the standard deviation of the first derivative of the CoP displacement signal within a trial and is often taken as measure of stability with greater RMS values indicating less stable balance.

EMG for the right soleus, gastrocnemii medialis and lateralis for the triceps surae (TS) and the tibialis anterior (TA) were collected at a rate of 2000 Hz (Bortec Electronics, Calgary, AB, Canada). All data were time synchronized with CoP-based measurements. Electrodes were placed in line with the muscle fibers and on the muscle belly. Inter-electrode distance was controlled at 2.5 cm. EMG activity was quantified using as root mean square algorithm with a 250-ms moving window (overlap of 125 ms) for the entire 30 s of each trial. The sum of EMG activities of the three muscles composing the TS was used to quantify plantar-flexor activity. EMG activity during cooling was normalized to the EMG activity in the standing control condition (that is, vision, no-cooling, no-vibration; mean activity of all trials of a subject).

To determine the possible increase of muscle co-activation after cooling procedure, the co-activation index was calculated as follow: co-activation index$= [(2 \times \widehat{EMG})/\sum EMG] \times 100$, where the $\widehat{EMG}$ is the common area of rectified EMG activity of TS and TA normalized by the maximal activity of the respective muscles in the control condition, and $\sum EMG$ is the sum of the rectified EMG activity of TS and TA normalized by the maximal activity of the respective muscles in the control condition.

2.6. Statistical analysis

Statistical analysis was performed using the Statistica software suite (version 7.0, StatSoft, Tulsa, Oklahoma, USA). Means ± SDs are