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Physical and Sensory Perturbations Changed Joint Regulations in Control of Posture: A Power Spectral Analysis

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ABSTRACT

Background: Standing on an unstable platform needs more effort from neuro-musculoskeletal system. This study was about to highlight the joint regulations in keeping balance, while standing on an unstable platform using spectral analysis.

Methods: Thirteen healthy young males were participated in this cross-sectional study to stand on an unstable platform with two levels of support stiffness, two visual, and three cognitive dual-task conditions. Motion analysis was utilized to measure postural regulations at the lower extremity joints. Power spectral analysis was applied on the joint rotations to discriminate the joint behaviors in different standing conditions.

Results: Results showed that the body used higher levels of postural adjustment by more joint regulations as the standing conditions became more difficult. Support stiffness of the platform and vision were effective in keeping balance ($P<0.05$), while the dual cognitive tasks had no significant effect ($P>0.05$). In simpler standing conditions, the ankle-hip strategy was responsible for body stabilization in lower frequencies. However, increasing the standing difficulty by eliminating the vision or use of looser support of the platform was led to the predominance of ankle strategy.

Conclusion: Standing in different conditions prevailingly relied on the ankle strategy. The enhancement of postural difficulty may revert to dominantly use the ankle strategy.

Introduction

Stable standing involves neural and musculoskeletal efforts under the control of central nervous system (CNS). CNS employs two principal strategies in maintaining the posture i.e., postural stiffening and postural adjustment. The stiffening of posture refers to the increase in the joints' rigidity by co-contraction of the acting muscle groups. In contrast, the postural adjustment strategy allows the joints to move in a controlled range of motion to overcome the perturbation [1].

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These postural strategies may include the traditional account of joint strategies e.g., ankle, hip, and ankle-hip strategies [2, 3]. For example, in the ankle strategy, the body seems to sway only around the ankle joint, whereas the hip muscle groups stiffen this joint by considerable activation levels [4].CNS, in other words, often uses multi-joint coordination in response to the perturbations [5], in which the roles of joints may vary during the strategies.

The various sets of conditions like physical, sensory, cognitive, etc., can change CNS decision during the selection of one postural strategy and the roles of the joints during the multi-joint coordination of the posture. The literature includes several studies that investigated the effects of physical (e.g., unstable standing platforms, single-leg standing, etc.) [6-8], sensory (e.g., visual, vestibular, and proprioception) [9-11], and cognitive (psychological, memorial, arithmetic, etc.) [7, 12-14] interventions on the postural stability and joint coordination.

The majority of previous studies concentrated on collective parameters of standing like excursions of the center of pressure (CoP) and some metrics based on its variations [15, 16]. But the postural adjustments are revealed in terms of joint rotations, specifically in response to physical perturbations applied to the support surface platform. It was shown that CNS might employ multi-joint control against the physical perturbations [5]. Besides, joint strategies to keep balance were re-regulated in simultaneous application of sensory and physical perturbations [9].

To the author's knowledge, none of the previous studies have investigated the simultaneous effects of physical, sensory, and cognitive difficulties in standing on the joint mechanisms and postural strategies of healthy individuals. Also, considering these parameters may postulate a level of difficulty for the CNS to control the posture [17, 18]. Nevertheless, the levels of joint regulations during postural adjustment may not necessarily accord to the postural difficulties.

Therefore, this study aims to investigate the role of joint regulations during multi-joint coordination of posture in response to physical, visual, and cognitive perturbations in different levels using the frequency-domain power spectral analysis. The rationale to use this technique is its ability to highlight the relative contribution of joint regulations in a multi-joint control of posture [5, 9, 19]. It was hypothesized that by the increase in the standing difficulties i) the ankle strategy replaced by the hip strategy, and ii) the postural stiffening strategy replaced by the postural adjustment strategy.

Methods

Subjects

Thirteen healthy young males (age: 26.8±3.8 years, weight: 74.2±8.9 kg, height: 175±6 cm) participated in this cross-sectional observational study from university students. All of them had no history of neuro-musculoskeletal disorders. None of them was a member of professional sports teams. The participants were aware of the test protocol by either verbal or written explanations. Informed consent was obtained from all of them. The test protocol was prepared based on the declaration of Helsinki, which the ethics committee approved of medical experiments of AJA University of Medical Sciences.

Procedure

The participants were asked to stand barefoot on a rocker board (formed by a 40×40 cm plate on top of five semi-ellipses along the anterior-posterior direction with minor and major axes as 10 and 15 cm, respectively), which was made of acrylic glass. They were also asked to cross their arms and focus on keeping the balance. The participants were familiarized with the set-up specifically for finding a comfortable place for their feet before the experiments. The initial standing of them was provided with the aid of the examiners. Two pairs of springs located under the front and rear parts of the plate (5 cm away from the edges) have supported the platform (Figure 1). Two stiffness levels were considered for the platform as a high stiffness (HS: 3200 N/m) and low stiffness (LS: 1600 N/m), which the latter imposed a more difficult physical condition to the participants [7]. Besides, the normal visual condition i.e. eye-open (EO), the participants stand with eye-closed (EC) to confront another standing difficulty. To further challenge CNS in control of the posture, three levels of dual cognitive tasks were added to the test: i) no-cognitive questions (NC); ii) simple-cognitive questions (SC) like asking five girl names starting with letter 'b' in the participants' native Farsi language; iii) difficult-cognitive questions (DC) like asking five Iranian city names ending at the letter 'm' or five four-letter ones. Therefore, 12 standing difficulty levels (=2 support stiffness×2 visual×3 cognitive conditions) were defined and labelled as D1 to D12. It was presumed that stiffer springs under the platform, open eyes, and simpler cognitive dual tasks make easier conditions to control the posture. In contrast, looser springs, closing the eyes, and adding more difficult cognitive dual tasks make standing harder for the participants. Each difficulty level had three trials of standing on the unstable platform for 30 seconds. One-minute rest intervals separated trials to avoid muscular or mental fatigue.

Measurement

Postural adjustment in terms of rotations of the lower extremity joints, i.e., ankle, knee, and hip, was assessed using motion analysis. Five active LED markers were attached to the fifth metatarsal, lateral malleolus, lateral femoral condyle, greater trochanter, and acromion process (Figure 1). A high-speed camera (Casio® EX-ZR20, Tokyo, Japan) captured the motions of the markers in the sagittal plane with 120 frames/s. A customized image processing code attained marker motions and then

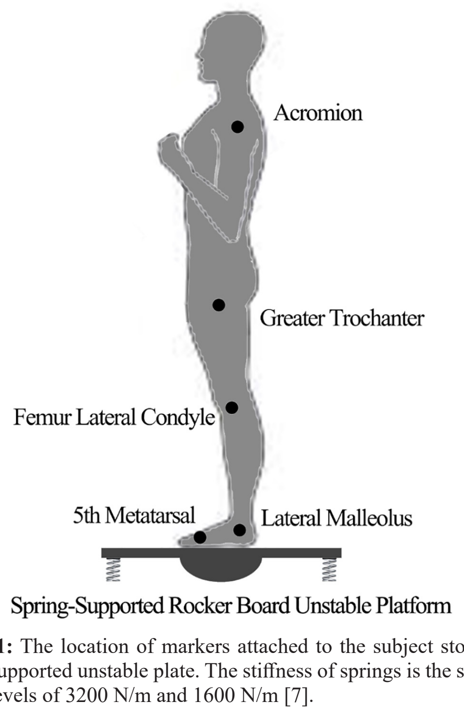

Figure 1: The location of markers attached to the subject stood on a spring-supported unstable plate. The stiffness of springs is the same but in two levels of 3200 N/m and 1600 N/m [7].

the angle of the joints against the test time. Excursions of the center of mass (CoM) were also calculated using anthropometric data of each participant.

Data Analysis

The power spectral analysis, in general, shows the strength of the variations (energy) as a function of frequency. In other words, it indicates variations at which frequencies are strong or weak. Hence, the power of two or more joints was compared to show the predominance of the joint mechanisms in different difficulties in standing. The power spectral analysis of the kinematics of joints and the CoM excursion time-series was calculated using the Bartlett kernel weighting method with parameters c=0.5 and e=0.334. The mean frequency (f_{mean}) as a factor of spectral widening was also calculated based on

$$f_{mean} = \frac{\int_{f_i}^{f_f} f.\mathrm{P}(f)\mathrm{d}f}{\int_{f_i}^{f_f} \mathrm{P}(f)\mathrm{d}f}$$

Where f and P denote frequency and power. The integrations were calculated from initial (f_i=0) to final frequency (f_f=50 Hz). Here, the mean frequency was a measure of postural strategy whose greater values (i.e., faster movements) indicate more adjustments than stiffening. Besides, the frequency in which ankle and hip powers are crossing was labelled as changing frequency to indicate the dominance of the standing strategies.

Statistical Analysis

A linear mixed model analysis of variance (ANOVA) was conducted to assess the effects of support stiffness, vision, and cognition on mean frequency values. The confidence interval was set as 95%.

Results

Figure 2 shows the power spectral density functions of ankle, knee, and hip rotations and the CoM excursions averaged among the participants. The averaged powers of the ankle are distinguishable into three difficulty bundles. The first three difficulties (on stiffer springs, open eyes) owned the lowest power, while the most difficult standings (closed eyes on looser springs) had the highest spectral densities. Such an eminent distinction among the difficulties is not observed in the averaged powers of knee and hip. The averaged CoM as the collective parameter of standing also distinguished two bundles of the first nine difficulties and the last three ones.

Figure 3 indicates the mean frequencies of all difficulty levels for three joint rotations and the CoM excursions. The mean frequency of ankle is more sensitive to the changes in standing difficulties ($P<0.031$ for EO, $P<0.002$ for EC) than the knee, hip, and CoM (all, $P>0.05$). Ankle rotations' mean frequency reduces with an increase in the presumed difficulty levels. Lower stiffness of supporting springs under the platform caused more significant decrease of the ankle to mean frequencies ($P<0.031$). The elimination of visual feedback also reduces the mean frequency in ankle rotations ($P=0.037$ for HS, $P<0.003$ for LS). There is no significant effect of cognition involvement on the mean frequency values ($P>0.05$).

Power spectral densities of ankle and hip are compared in some selected difficulty levels in Figure 4. By increasing the presumed standing difficulty (from D1 to D12) the ankle and hip powers had a replacing behavior that is the hip owns higher powers in the early frequencies than the ankle. However, ankle powers in the higher frequencies enhance to be greater than the hip. The frequency that these powers are crossing each other to change their dominance is labelled as the changing frequency (see black inverted triangles in Figure 4). The changing frequency is also reduced by standing in more difficult conditions so that the ankle's power is thoroughly greater than the hip powers in all frequencies from the D9 level.

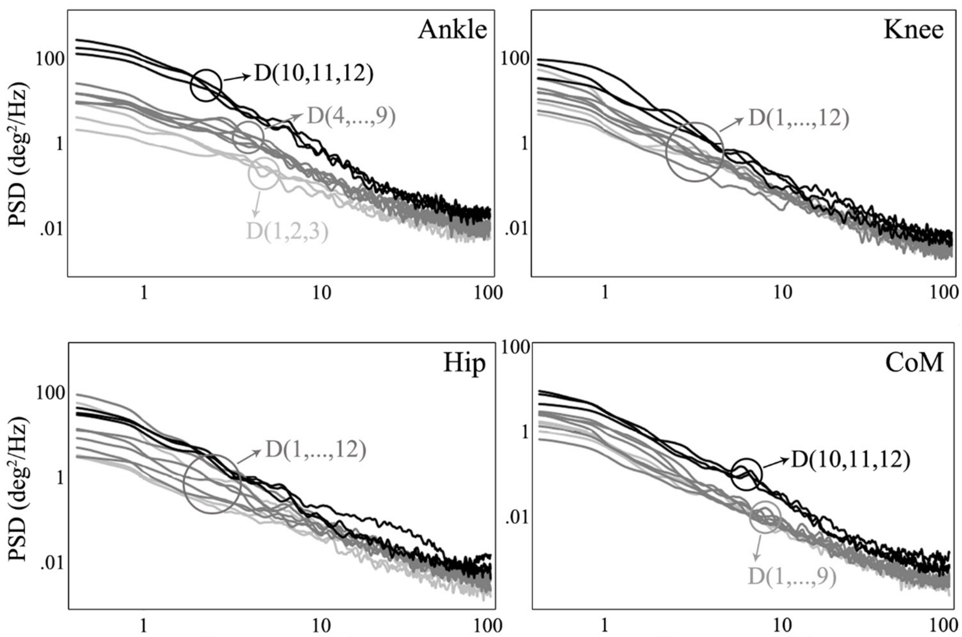

Figure 2: Averaged power spectral density values against frequency for ankle, knee, hip, and the center of mass (CoM) motions. Circles divide adjacent bundles of the presumed standing difficulties.

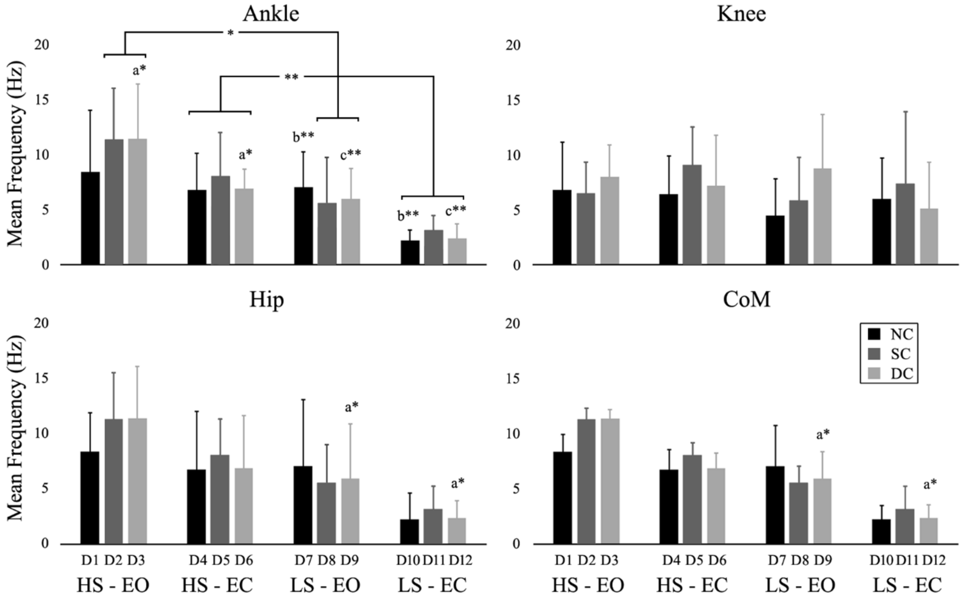

Figure 3: Mean frequency values for ankle, knee, hip and the center of mass (CoM) motions in all twelve standing difficulties (D1, D2, …, D12). Significant differences are marked as * for P<0.05 and ** for P<0.01. Letters a, b and c denote significant pairs. Abbreviations: HS=high spring stiffness, LS=low spring stiffness, EO=eyes open, EC=eyes closed, NC=no cognitive, SC=simple cognitive, DC=difficult cognitive.

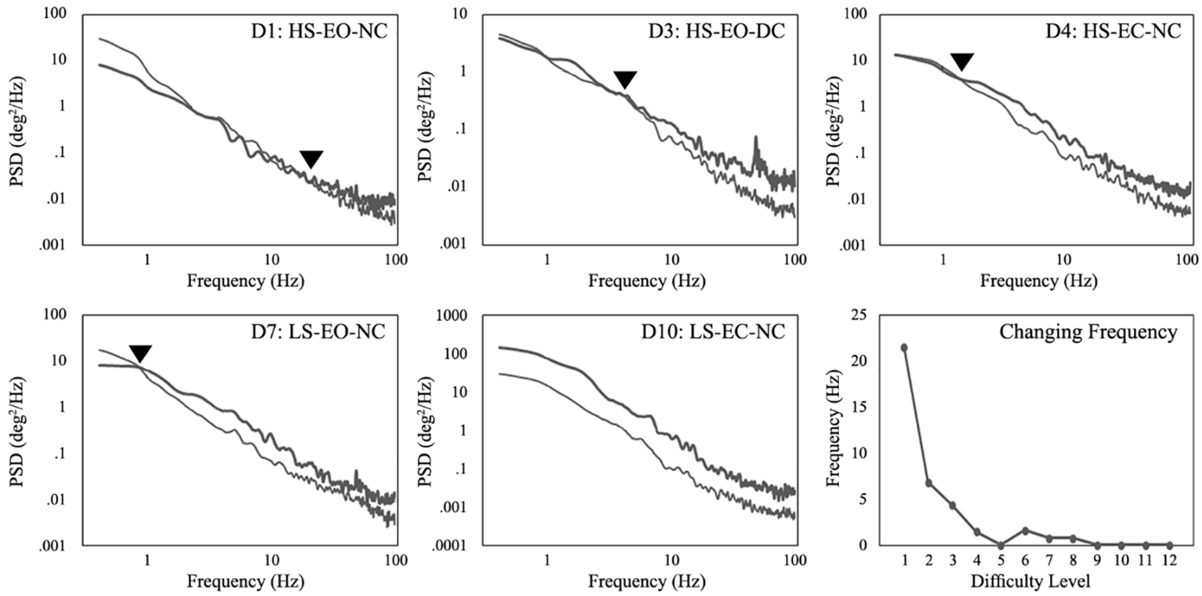

Figure 4: Power spectral density values against the frequency for five selected standing difficulties D1, D3, D4, D7, and D10. Black inverted triangles indicate the changing frequency in which the ankle power (thick graph) overwhelms the hip (thin graph). The bottom-right graph plots the changing frequency for all standing difficulty levels. Abbreviations: HS=high spring stiffness, LS=low spring stiffness, EO=eyes open, EC=eyes closed, NC=no cognitive, DC=difficult cognitive.

Discussion

This study challenged the control of the posture of healthy young individuals with simultaneous physical, sensory and cognitive perturbations. Twelve difficulty levels in standing were defined from the easiest (open eyes, without cognitive loads, and on a more supported wobbling platform) to the hardest (closed eyes, with cognitive loads, and on a less supported wobbling platform) conditions. It was expected that this step-by-step augmentation of the difficulty to the participants results in changing the contribution of the joint mechanisms and the overall postural strategy.

The main outcome of study was that only the ankle behaves differently against the applied postural difficulty levels (D1, … D12) in terms of the power diagrams. The power spectral of knee and hip did not change using different difficulty levels. The changing frequency which was defined as the cross-point between the ankle and the hip power spectral functions was also lower in the easiest levels. The lower changing frequency meant that the ankle is the dominant joint mechanism in control of the posture. It was showed that the CNS relies on the ankle only in the easiest conditions. By augmenting the difficulty of participants' posture, the ankle mechanism could no longer contribute to keep the balance alongside the hip. The hip mechanism was the lonely joint that provided stability during the more difficult levels of standing. In response to the perturbations, it implied that the CNS preferred to rely on the hip mechanism in all cases to permit the body to rotate around the ankle like an inverted pendulum. The participants in this study were all healthy and young which have strong enough calf musculature without any sensory deficit. The literature conventionally argued that the ankle-hip strategy emerges when the magnitude of perturbations grows [20]. Recent studies, however, showed that the standing strategies depend on the available sensory information, task, or perturbation [9]. The ankle mechanism played the largest role in controlling the body posture in higher frequencies, and the hip strategy contributed to the postural adjustment in lower frequencies. In other words, the ankle mechanism was responsible for the fast adjustment of the posture against the faster applications of perturbation while the hip could not react rapidly and contributed to a collaboration with the ankle, while the need to adjust is roughly slower. Creath et al. reported that the in-phase collaboration between the ankle and hip occurs in frequencies below 1 Hz [9].

The slower reactions of hip during the control of posture may be due to the distance of this joint to the perturbation site below the ankle [9]. The ankle, either due to its nearness to the perturbation or the calf muscle proprioceptive feedback, mainly contributed to provide stability on the movable platform while the hip might perform final tuning of the posture to limit the CoM within the narrow base of support [7]. The ankle supporting muscles, especially in the calves, are exceptionally either the sensors or the actuators during the control of the posture [21]. The proprioceptive signals from the reflexes are among the fastest signaling in the body, making the ankle strategy adjust the posture quickly, which was emphasized in terms of its high mean frequencies. Calculating the mean frequency was due to present a measure for strategy change in the postural control [22]. Two main strategies of postural stiffening against adjustment were investigated. By looking at the collective kinematics, i.e. the CoM mean frequency, there was no considerable strategy change in the body since none of the perturbations caused significant alternation in the CoM movement. Nevertheless, CNS decreased the ankle's mean frequency, which meant stopping postural adjustment and choosing the stiffening strategy. The other joints and CoM continued their first-chosen strategy i.e., the postural adjustment. Only the removal of vision in the less supported platform while asking the most difficult cognitive question could significantly change the postural strategy from the adjusting to the stiffening. In the other eleven conditions, the CNS preferred to adjust by the relatively fast movement of the hip and the CoM overall. The cognitive perturbations that were of the memorial type had no significant effect on the joint behaviors and body strategy. There is no consensus on the role of cognitive interference in postural control, although some previous studies have stated reported postural instabilities by applying the cognitive perturbations [10-17]. The reason behind this controversy may be due to the diversities existed in the cognitive tasks (numerical, mental calculations, visual, verbal, memory and recall, sustained attention, text, etc.) [11, 12, 16, 17], postural assessing tasks (often contained quiet vs. perturbed standing, open or closed eyes, etc.) [10, 13, 15], and the nature of the acquired data (center of mass vs. center of pressure) [14, 15]. The outcomes of this study regarded that the cognitive loads were in accordance with ref [7].

The removal of vision caused a decelerating effect on the joint mechanisms. The mean frequency of ankle in both spring supports and the hip and CoM kinematics only in the less support platform condition decreased significantly to imply the strategy from the postural adjustment to the stiffening of the joints. The elimination of visual feedback led to stability reduction during different tasks of standing in the literature as coincided with this study's findings [19, 23]. In contrast, some other investigations declared non-significant changes in the mean frequency of body sway by removing the vision [22]. However, electromyography of the leg muscles showed more muscle activation to maintain the posture in the absence of vision [24, 25].

Standing on an unstable platform is, per se, a difficult physical task even for healthy individuals because the body should confine the vertical projection of the CoM within a smaller base of support [6]emsAsXml and need more neuro-muscular efforts [26]. The base of support was a diamond-shaped region formed by two corners of spring locations and two lateral midpoints of the contact regions between the ground and the bottom faces of the semi-ellipses. Hence, CoM should be kept within a triangle with its forepart vertex to prevent forward falling. Standing in such a difficult condition may vanish the role of other perturbations like the cognitive loads. Maybe in an easier physical condition like quiet or single-leg standing, the effects of the cognitive loads could be disclosed [7].

The present study was faced with some limitations. The participants' knowledge of the cognitive questions might be different, though the test was designed to reduce this effect by asking more routine questions while respecting difficulty level. The difficulty in cognitive questions was not based on the paucity of answers but on the level of mental involvement.

Conclusion

The test conditions may challenge using the ankle-hip strategy in balance as a conventional account. This study showed that during standing on unstable support, which was inherently so difficult to employ the ankle-hip, more enhancement of the postural difficulty might revert to the dominance of the ankle strategy. Applying the physical and sensory perturbations changed the adjusting postural control to the stiffening. The body in the easier standing tasks with slower environment changes used the postural adjustment with considerable reliance on the ankle strategy, while imposing faster and more difficult postural conditions caused joint stiffening and the role-playing of the hip strategy. Although this study was done on healthy young individuals, the cognitive loads had no effects on the posture. It may highlight using both internal and external focus in the fall-preventing exercises that should consider sensory re-training rehabilitation programs. Further studies are needed to shed light on the details of these factors on the other populations with specific disorders.

Conflict of Interest: None declared.

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