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Effects of joint immobilization on standing balance

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ABSTRACT

We investigated the effect of joint immobilization on the postural sway during quiet standing. We hypothesized that the center of pressure (COP), rambling, and trembling trajectories would be affected by joint immobilization. Ten young adults stood on a force plate during 60 s without and with immobilized joints (only knees constrained, CK; knees and hips, CH; and knees, hips, and trunk, CT), with their eyes open (OE) or closed (CE). The root mean square deviation (RMS, the standard deviation from the mean) and mean speed of COP, rambling, and trembling trajectories in the anterior–posterior and medial–lateral directions were analyzed. Similar effects of vision were observed for both directions: larger amplitudes for all variables were observed in the CE condition. In the anterior–posterior direction, postural sway increased only when the knees, hips, and trunk were immobilized. For the medial–lateral direction, the RMS and the mean speed of the COP, rambling, and trembling displacements decreased after immobilization of knees and hips and knees, hips, and trunk. These findings indicate that the single inverted pendulum model is unable to completely explain the processes involved in the control of the quiet upright stance in the anterior–posterior and medial–lateral directions.

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1. Introduction

During upright quiet standing the body has often been modeled as a single inverted pendulum, pivoting about the ankle joints (Gage, Winter, Frank, & Adkin, 2004; Winter, Patla, Prince, Ishac, & Gielo-Perczak, 1998). The premise of the single inverted pendulum model is that the body above the ankles behaves as a rigid structure. The use of this model to represent balance maintenance in quiet standing has been supported by kinematic, kinetic (Gage et al., 2004; Karlsson & Persson, 1997), and EMG (Gatev, Thomas, Kepple, & Hallett, 1999) measures in both the sagittal and frontal plane (Winter, Prince, Frank, Powell, & Zabjek, 1996). However, most of the kinematic studies have shown small angular displacements at joints above the ankles (Gage et al., 2004; Gatev et al., 1999). For example, Gage and collaborators (Gage et al., 2004) reported that knee joint movements were larger as compared to ankle joint displacement in quiet standing but they still considered the single inverted pendulum model a good representation of quiet standing in humans. Conversely, it has also been claimed that small angular displacements at joints above the ankles play an important role in the control of quiet upright stance and their contribution should not be ignored (Aramaki et al., 2001; Bardy, Marin, Stoffregen, & Bootsma, 1999; Creath, Kiemel, Horak, Peterka, & Jeka, 2005; Day, Steiger, Thompson, & Marsden, 1993; Fitzpatrick, Rogers, & McCloskey, 1994; Krishnamoorthy, Yang, & Scholz, 2005; Nicholas, Doxey-Gasway, & Paloski, 1998).

Recently, Hsu, Scholz, Schöner, Jeka, and Kiemel (2007) and Krishnamoorthy et al. (2005) reported that stabilization of a reference position (assumed to be described by the position of the center of mass, COM) was achieved by coordination of several joints along the human "pendulum" when participants stood quietly on a normal and on a narrow base of support. Similar findings were observed when sudden perturbations were applied to the participants in quiet stance (Alexandrov, Frolov, Horak, Carlson-Kuhta, & Park, 2005), when supra-postural tasks were performed in quiet standing (Bardy, Oullier, Bootsma, & Stoffregen, 2002; Bardy, Oullier, Lagarde, & Stoffregen, 2007; Bardy et al., 1999), during fast-forward voluntary trunk bending movements (Alexandrov, Frolov, & Massion, 2001), and during whole-body voluntary movements (Freitas, Duarte, & Latash, 2006). In addition, Kuo and Zajac (1993) found that the "ankle strategy" involving rotation about the ankles only (Nashner, 1981) requires more muscle activation than the "hip strategy" (two-segment inverted pendulum pivoting about the hip and ankle joints) for a given amount of horizontal acceleration. Hence, the hip strategy is more effective at controlling the COM position with minimal muscle activation when comparing to the "ankle strategy".

Another approach to investigate the adequacy of the single inverted pendulum model to describe the control of the upright stance and, concurrently, the role played by the joints above the ankles in this control is to prevent the movement of those joints while maintaining a quiet stance. To date, only two studies investigated the effect of preventing movements of the joints above the ankles on postural control (Aramaki et al., 2001; Fitzpatrick et al., 1994), and only Fitzpatrick et al. (1994) measured the amount of postural sway in the anterior–posterior direction after joint immobilization, whereas the effect of joint immobilization on medial–lateral direction was not assessed. They observed that when a rigid splint prevented the movement of all joints above the ankles, the magnitude of the ankle angular sway increased significantly.

The most common measure of postural sway in quiet standing is the center of pressure (COP) migration derived from force plate data. COP is the point of application of the resultant of vertical forces acting on the surface of support (Duarte & Zatsiorsky, 2002). Several methods have been proposed to decompose the COP displacement, commonly called stabilogram, with the intention to understand the mechanisms of postural control during quiet standing (Baratto, Morasso, Re, & Spada, 2002; Bottaro, Casadio, Morasso, & Sanguineti, 2005; Collins & De Luca, 1993; Dijkstra, 2000; Frank, Daffertshofer, & Beek, 2000; Winter et al., 1998; Zatsiorsky & Duarte, 1999, 2000). Zatsiorsky and Duarte (1999) proposed a method to decompose the COP trajectory based on the idea that the body sways due to two reasons: (a) migration of the reference point with respect to which the equilibrium is instantly maintained (*rambling*), and (b) oscillation of the body with respect to the moving equilibrium reference (*trembling*). They found that the trembling migration correlates highly (and negatively) with the horizontal ground reaction force while such a correlation does not exist for the rambling.

These findings were interpreted as evidence that the trembling represents a deviation from the instant equilibrium position corrected via the horizontal ground reaction forces inducing the COM acceleration in the direction opposite to the deviation while the central controller does not correct the COP migrations associated with the rambling. According to the rambling and trembling hypothesis, the rambling and trembling reflect two distinct processes contributing to the control of body sway. The rambling trajectory may be related to supraspinal processes that are involved in the control of the migration of the instant reference point. The trembling may be a result of both, the action of spinal reflexes and changes in the intrinsic mechanical properties of the muscles and joints. In particular, the authors (Zatsiorsky & Duarte, 1999, 2000) suggested that the trembling was due to the moment at the ankle joints during quiet standing.

The analysis of the trajectories of the COP and its components during quiet standing while the joints above the ankles are immobilized could provide additional information regarding the effectiveness of the single inverted pendulum model and also the role played by the above-the-ankle joints in the control of posture. Therefore, the purpose of this study was to examine the contribution of the main joints (ankle, knee, hip, and joints of the trunk) to the control of quiet upright stance. Specifically, the current study investigated the COP, rambling, and trembling behaviors when the knees, hips, and lower and medium portion of the trunk were constrained and the body balance had to be controlled exclusively by the non-constrained joints, specifically the ankle joints. We hypothesized that if the body behaves as a single inverted pendulum, the joint constraints will have a minor or no effect on the COP, rambling, and trembling variables, whereas significant changes in the COP, rambling, and, principally, in the trembling would indicate that the single inverted pendulum model cannot accurately explain the processes involved in the control of quiet upright stance.

Because the hip abductors/adductors, in addition to the ankle invertors/evertors, have been considered responsible for controlling the medial–lateral movements (Winter et al., 1996), it was expected that the hip joint constraints would affect body sway in the frontal plane as well. Specifically, we predicted an increase in postural sway in medial–lateral direction mainly when hip and trunk were immobilized. In addition, this study investigated the combined effect of immobilization and vision on the sway in both directions (sagittal and frontal), while participants stood with their eyes open or closed.

2. Method

2.1. Participants

Ten healthy adults, five males and five females, without any known neurological and musculoskeletal disorders, or balance problems, participated in this study. The participants' mean (±1 SD) age, body mass, and height were 28.3 (±4.6) years, 66.7 (±4.6) kg, and 169 (± 9) cm, respectively. Prior to the testing, the participants signed the informed consent form in accordance with the policies established by the Office for Regulatory Compliance of The Pennsylvania State University.

2.2. Procedures

The participants were instructed to stand upright as still as possible in bipedal stance on a 40×80 cm force platform (model 4080S, Bertec, Worthington, OH, USA). They stood barefoot with their feet positioned side-by-side at a comfortable width (about shoulder width), and arms placed in a relaxed position at the body's sides. Also, they were instructed to maintain the head erect and to look at a circular target (radius = 2.5 cm) positioned approximately 120 cm in front of them at eye level.

During the experiment the participants were submitted to four joint immobilization conditions: no constraint (NC), constraint of the knees (CK), constraint of the hips and knees (CH), and constraint of the trunk, hips, and knees (CT), and two visual conditions, open and closed eyes (OE and CE, respectively). Fig. 1 depicts the different levels of immobilization. The joint constraints were applied for each limb separately.

The joints were tightly immobilized by splints, casts, and duct tape. The knees constraints started from the 2/3 superior part of the shank and ended at the 2/3 inferior part of the thigh, with each knee

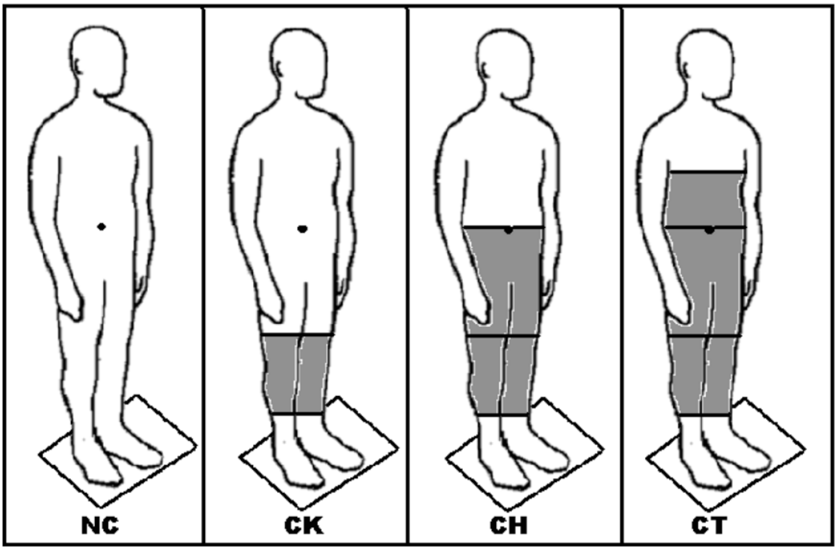

Fig. 1. Schematic representation of the different immobilization conditions. No constraint (NC), constraint of the knee joints (CK), constraint of the knee and hip joints (CH), and constraint of the knees, hips, and trunk (CT).

immobilized separately. Four splints, one on the anterior, one on the posterior, one on the medial, and one on the lateral side, were placed vertically around each knee. After the splints were positioned, cast tapes were placed to fix the splints and finally duct tape was placed around each knee to increase the resistance and prevent any knee's flexion–extension movement. The hip was immobilized from 1/3 of the proximal part of the thigh to 1/3 of the inferior part of the trunk at the navel level. In the same way as the knee constraints, splints were placed around the thighs, pelvis, and the inferior portion of the trunk; fixed by cast tapes and reinforced by duct tape. Finally, the trunk was immobilized from the navel line to the sternum xiphoid process, also using splints, casts, and duct tape. The immobilizations assured that joint movements around knees, hips, and trunk were completely restricted.

Six trials were performed in each immobilization condition, three trials with eyes open and three with eyes closed. The order in which each visual condition was presented in each trial was randomized across participants: a trial with open (close) eyes was always followed by a trial with eyes closed (open). During each trial the participants stood quietly for 60 s. Five participants started the experiment with the trunk, hips, and knees immobilized (CTOE and CTCE condition) and had the immobilization hardware removed in a top-to-down sequence (CT–NC). The other five participants started without any constraint; the immobilization was applied in a down-to-top sequence (NC–CT). This procedure was used to avoid fatigue effects on body sway.

2.3. Data acquisition and analysis

Data were recorded using a PC with a 12-bit A/D board (model AT-MIO-64E-3, National Instruments Corporation, Dallas, TX, USA) controlled by a special code written in LabView software (LabView 6.1; National Instruments, Dallas, TX, USA). The force platform used during the experiment provided information about the three forces and three moment components. The signals were used to calculate the center of pressure (COP) displacement in the anterior–posterior (COP_{AP}) and medial–lateral direction (COP_{ML}). The data were recorded with a sampling frequency of 100 Hz. The data analysis was performed using MATLAB software (MATLAB 6.5, The MathWorks, Natick, MA, USA). Data from horizontal forces (F_y and F_x) and COP (COP_{AP} and COP_{ML}) time-series were low-pass filtered with a zero-lag, fourth-order Butterworth filter with a cut-off frequency of 8 Hz.

Rambling and trembling time-series were determined using the procedures described previously by Zatsiorsky and Duarte (1999). A brief description of the analyses is provided below. At the instances when the horizontal force (F_{hor}) is zero ($F_{hor} = 0$) the body is instantaneously in an equilibrium state (Zatsiorsky & King, 1998). The instances when F_{hor} changed its sign were determined using local linear interpolation of the F_{hor} time-series. Then, the instant equilibrium points (IEP, i.e., the COP locations at the instances when the horizontal forces were zero) were identified. After this procedure, the IEPs were used to compute the rambling and trembling trajectories. The IEPs and the rambling and trembling trajectories were determined separately from COP_{AP} and COP_{ML} time-series.

The rambling trajectory was established by interpolating the discrete IEPs with a cubic spline function. According to the rambling–trembling hypothesis, the rambling represents migration of the reference point on the supporting surface with respect to which the body equilibrium is maintained. The trembling represents the deviation of the COP from the equilibrium position and it was determined by subtracting the rambling trajectory from the COP trajectory (for more details see Zatsiorsky & Duarte, 1999, 2000). Fig. 2 depicts an example of the F_{hor} time-series, the IEPs, and the COP, rambling, and trembling trajectories for a single trial in NCOE condition (anterior–posterior direction, 20 s).

The dependent variables analyzed in this study were root mean square deviation (RMS, the standard deviation from the mean) and mean speed of the COP, and the rambling and trembling displacement in the anterior–posterior (AP) and medial–lateral (ML) directions. Before calculating these variables, the very low frequencies were removed from the COP, rambling, and trembling time-series. Namely, COP, rambling, and trembling time-series were linearly detrended by subtracting their own best fit line from their respective time-series. The RMS in both directions was determined by calculating the standard deviation of each signal, i.e., the oscillations of the signals around their mean values. The mean speed was determined by dividing the total distance along the signal trajectory by the total recording time.

2.4. Statistical analyses

Before performing the statistical analyses, we normalized, for each individual participant, the values of RMS and mean speed of the COP, rambling, and trembling as percentage of their respective val-

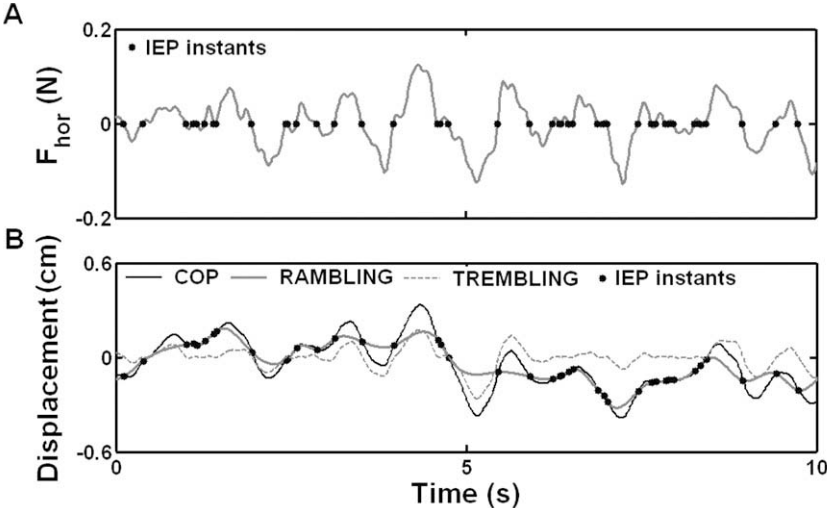

Fig. 2. Sequence of operations used for COP trajectory decomposition. In A, the horizontal force (Fhor) and the instances when $F_{hor} = 0$ (·) are presented. The COP trajectory, the COP position at the IEP instants (·), rambling trajectory (estimated by the cubic spline interpolation of the COP position at the IEP instants), and trembling trajectory (the difference between COP and interpolated rambling trajectories) are presented in B. Participant SS, female, age 29 yrs; Ht 1.61 m; Wt 52 kg.

ues measured in the NCOE condition (i.e., NCOE = 0%). For each variable, we subtracted the value of each one of the immobilization conditions by the value of the NCOE condition, divided the result by the value of the NCOE condition, and then multiplied by 100 [e.g., $((RMS_{CTOE} - RMS_{NCOE})/RMS_{NCOE}) * 100$]. The statistical analyses were performed in SPSS (version 10.1, Chicago, IL) using the normalized values averaged over all trials for each participant for all dependent variables (RMS and mean speed of the COP, rambling, and trembling time-series). To examine the effects of the joint immobilization (NC, CK, CH, CT) and vision (OE and CE) on each dependent variable, a total of four repeated measures two-way MANOVAs, two for AP and two for ML direction, were performed. When necessary, univariate analysis and post hoc tests with Bonferroni corrections were carried out. The significance level was set at .05. However, marginal effects ($p < .1$) were also considered in the analysis.

3. Results

All participants were able to stand with their joints immobilized. However, changes in postural sway due to joint immobilization were observed. Fig. 3 shows a stabilogram with a typical COP trajectory in each joint immobilization and visual condition. As can be seen, the COP displacements in the anterior–posterior (COP_{AP}) direction and in the medial–lateral (COP_{ML}) direction were differently influenced by the joint immobilization. These effects were observed for both visual conditions. Detailed statistical analyses of each variable of postural sway are presented below for each direction separately. Table 1 presents the non-normalized means and standard errors values in both directions.

3.1. Anterior–posterior direction

The results showed that postural sway in anterior–posterior (AP) direction was altered after immobilization of knees, hips, and trunk joints. Fig. 4 depicts the averaged normalized RMS and mean speed values of the COP (left-hand side), rambling (middle), and trembling (right-hand side) displacements in the AP direction.

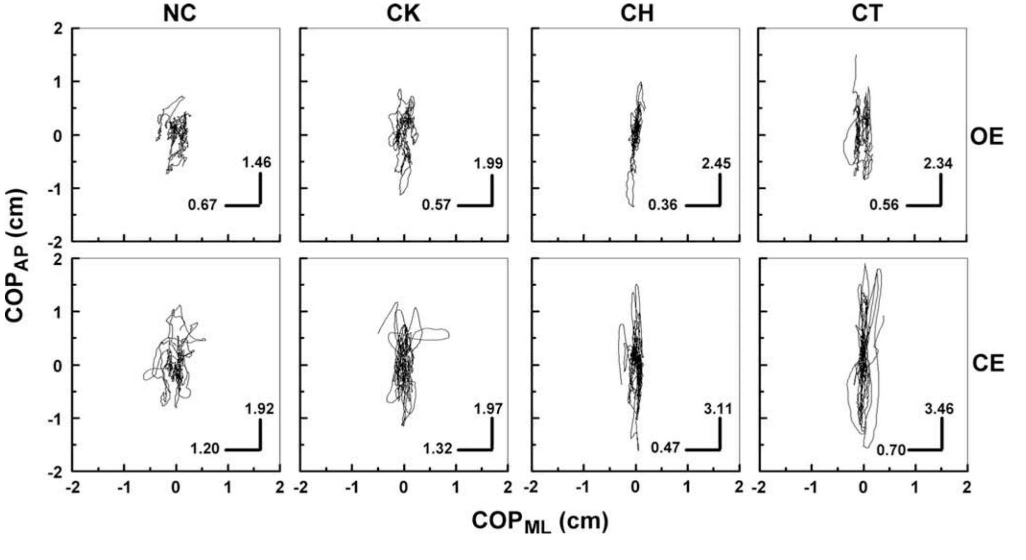

Fig. 3. A representative example of the results of the COP trajectory during all joints immobilization and visual conditions. Bars and numbers represent the standard deviation in the anterior–posterior (COP_{AP}) and medial–lateral (COP_{ML}) directions. Participant SS, female, age 29 yrs; Ht 1.61 m; Wt 52 kg.

Table 1
Mean (±S.E.) of the COP, rambling, and trembling RMS and mean speed for four immobilizations and two visual conditions.

Variables			Open eyes				Closed eyes			
			NC	CK	CH	CT	NC	CK	CH	CT
RMS (cm)	AP	COP	0.286 ± 0.023	0.271 ± 0.021	0.282 ± 0.020	0.278 ± 0.017	0.368 ± 0.032	0.384 ± 0.037	0.396 ± 0.035	0.423 ± 0.031
		Rambling	0.258 ± 0.021	0.239 ± 0.019	0.251 ± 0.019	0.246 ± 0.017	0.320 ± 0.030	0.322 ± 0.032	0.340 ± 0.035	0.353 ± 0.025
		Trembling	0.076 ± 0.008	0.083 ± 0.009	0.085 ± 0.009	0.084 ± 0.007	0.114 ± 0.009	0.143 ± 0.016	0.134 ± 0.007	0.157 ± 0.015
	ML	COP	0.132 ± 0.012	0.114 ± 0.012	0.082 ± 0.010	0.090 ± 0.014	0.164 ± 0.015	0.140 ± 0.015	0.101 ± 0.012	0.110 ± 0.016
		Rambling	0.115 ± 0.012	0.100 ± 0.012	0.071 ± 0.010	0.078 ± 0.014	0.140 ± 0.014	0.120 ± 0.015	0.088 ± 0.012	0.093 ± 0.016
		Trembling	0.045 ± 0.003	0.041 ± 0.003	0.031 ± 0.003	0.032 ± 0.004	0.058 ± 0.004	0.052 ± 0.003	0.035 ± 0.004	0.042 ± 0.003
Mean speed (cm s^{-1})	AP	COP	0.484 ± 0.045	0.507 ± 0.041	0.527 ± 0.056	0.518 ± 0.060	0.656 ± 0.061	0.739 ± 0.062	0.713 ± 0.066	0.792 ± 0.068
		Rambling	0.244 ± 0.014	0.349 ± 0.032	0.226 ± 0.025	0.243 ± 0.030	0.392 ± 0.020	0.285 ± 0.021	0.294 ± 0.029	0.327 ± 0.030
		Trembling	0.426 ± 0.038	0.170 ± 0.020	0.416 ± 0.040	0.414 ± 0.045	0.187 ± 0.016	0.611 ± 0.049	0.580 ± 0.055	0.656 ± 0.066
	ML	COP	0.275 ± 0.021	0.259 ± 0.025	0.234 ± 0.020	0.234 ± 0.021	0.318 ± 0.018	0.293 ± 0.024	0.251 ± 0.022	0.266 ± 0.019
		Rambling	0.172 ± 0.014	0.232 ± 0.019	0.157 ± 0.014	0.161 ± 0.015	0.291 ± 0.017	0.182 ± 0.020	0.163 ± 0.015	0.162 ± 0.015
		Trembling	0.300 ± 0.030	0.423 ± 0.034	0.274 ± 0.028	0.266 ± 0.024	0.543 ± 0.052	0.317 ± 0.031	0.285 ± 0.026	0.291 ± 0.024

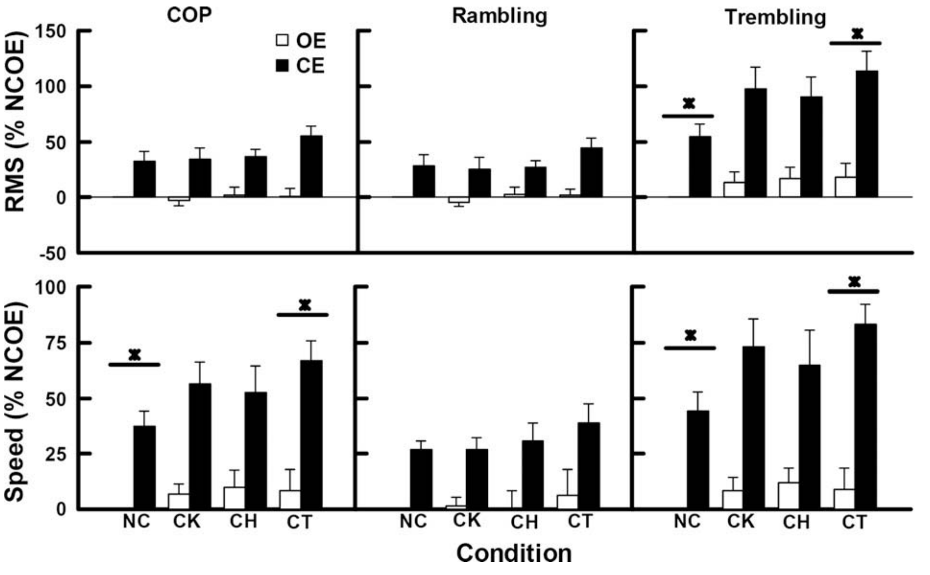

Fig. 4. The RMS and speed values of the COP, rambling, and trembling in the anterior–posterior direction averaged across participants. Values were normalized by the values of the NCOE condition (NCOE = 0%). Error bars indicate the standard error of the means. ∗ represents differences with $p < .05$.

3.1.1. Effect of immobilization on the RMS

The AP RMS of the COP, rambling, and trembling displacements averaged across joint immobilization and visual conditions are depicted in the upper panels of Fig. 4. MANOVA revealed main effects of joint immobilization [Wilks' Lambda = .477, $F(9,61) = 2.4$, $p < .05$, $\eta^2 = .21$] and vision [Wilks' Lambda = .07, $F(3,7) = 31$, $p > .001$, $\eta^2 = .93$], but no interaction between those factors [Wilks' Lambda = .634, $F(9,61) = 1.39$, $p > .05$, $\eta^2 = .14$] on the RMS in AP direction. Univariate analyses revealed a main effect of joint immobilization on the RMS of the trembling displacement [$F(3,27) = 4.29$, $p > .05$, $\eta^2 = .32$], and marginal main effects on the RMS of the COP [$F(3,27) = 2.55$ $p = .076$, $\eta^2 = .22$] and rambling [$F(3,27) = 2.49$, $p = .082$, $\eta^2 = .22$] displacements. Post hoc tests with appropriated Bonferroni corrections showed that the RMS of the trembling displacement was larger when the knee, hips, and trunk were constrained (CT condition) as compared to when no constraint was imposed to the joints (NC condition). Although a marginal effect of joint immobilization on the RMS of the COP and rambling displacements was identified, no differences among joint immobilization conditions were observed. With respect to the main effect of vision, univariate analysis indicated that the RMS of the COP [$F(1,9) = 56$, $p < .001$, $\eta^2 = .86$], rambling [$F(1,9) = 27$, $p < .005$, $\eta^2 = .75$], and trembling [$F(1,9) = 48$ $p < .001$, $\eta^2 = .84$] displacements were larger when participants kept their eyes closed (CE) as compared to when they kept their eyes open (OE).

3.1.2. Effect of immobilization on the mean speed

The AP mean speed of the COP, rambling, and trembling displacements averaged across joint immobilization and visual conditions are depicted in the lower panels of Fig. 4. For these variables, MANOVA revealed a marginal main effect of joint immobilization [Wilks' Lambda = .572, $F(9,61) = 1.75$, $p = .098$, $\eta^2 = .17$] and a main effect of vision [Wilks' Lambda = .09, $F(3,7) = 24$, $p > .001$, $\eta^2 = .91$], but no interaction between those factors [Wilks' Lambda = .72, $F(9,61) = .99$, $p > .05$, $\eta^2 = .10$]. Univariate analyses revealed main effects of joint immobilization on mean speed of the COP [$F(3,27) = 3.77$, $p = .022$, $\eta^2 = .29$] and trembling [$F(3,27) = 4.78$, $p = .008$, $\eta^2 = .35$] displacements, but not on the mean speed of the rambling [$F(3,27) = .88$, $p = .462$, $\eta^2 = .21$] displacement. For both, COP and trembling, post hoc tests revealed that the mean speed of the COP and trembling displacements was larger in CT than in NC condition. Regarding the main effect of vision, univariate analysis indicated that the main speed of the COP [$F(1,9) = 70$, $p < .001$, $\eta^2 = .89$], rambling [$F(1,9) = 70$, $p < .001$, $\eta^2 = .89$], and trembling [$F(1,9) = 56$, $p < .001$, $\eta^2 = .86$] displacements was larger in the CE than in OE condition.

3.2. Medial–lateral direction

With respect to postural sway in medial–lateral (ML) direction, the results showed that when the participants had their knee and hip joints and their knees, hips, and trunk immobilized their postural sway in ML direction was altered. Fig. 5 depicts the averaged normalized RMS and mean speed values of the COP (left-hand side), rambling (middle), and trembling (right-hand side) displacements in the ML direction.

3.2.1. Effect of immobilization on the RMS

The ML RMS of the COP, rambling, and trembling displacements averaged across immobilization and visual conditions are depicted in the upper panels of Fig. 5. MANOVA revealed significant main effects of joint immobilization [Wilks' Lambda = .346, $F(9,61) = 3.7$, $p < .005$, $\eta^2 = .30$] and vision [Wilks' Lambda = .214, $F(3,7) = 8.55$, $p < .05$, $\eta^2 = .79$] on RMS in ML direction. No interaction between joint immobilization and vision [Wilks' Lambda = .713, $F(9,61) = 1$, $p > .05$, $\eta^2 = .41$] was observed. Univariate analysis revealed a significant effect of joint immobilization on the RMS of the COP [$F(3,27) = 9.24$, $p < .001$, $\eta^2 = .51$], rambling [$F(3,27) = 7.02$, $p < .005$, $\eta^2 = .43$], and trembling [$F(3,27) = 10.6$, $p < .001$, $\eta^2 = .54$] displacements. Post hoc tests revealed that the RMS of COP and the rambling and trembling displacements were smaller in the CH and CT than in the NC condition. Regarding vision, results revealed that RMS of the COP [$F(1,9) = 23.73$, $p < .005$, $\eta^2 = .73$], rambling [$F(1,9) = 17.2$, $p < .005$, $\eta^2 = .66$], and trembling [$F(1,9) = 22.4$, $p < .005$, $\eta^2 = .71$] displacements were larger in the CE than in the OE condition.

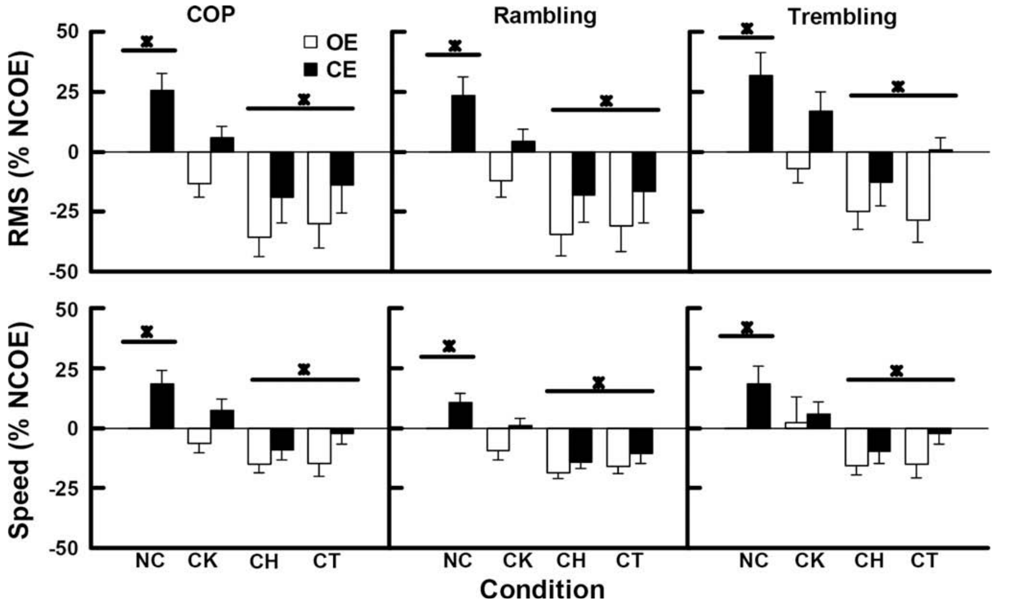

Fig. 5. The RMS and speed values of the COP, rambling and trembling in the medial–lateral direction averaged across participants. Values were normalized by the values of the NCOE condition (NCOE = 0%). Error bars indicate the standard error of the means. * represents differences with $p < .05$.

3.2.2. Effect of immobilization on the mean speed

The ML mean speed of the COP, rambling, and trembling displacements averaged across immobilization and visual conditions are depicted in the lower panels of the Fig. 5. MANOVA revealed significant effects of joint immobilization [Wilks' Lambda = .35, $F(9,61) = 3.66$, $p < .005$, $\eta^2 = .30$], and vision [Wilks' Lambda = .271, $F(3,7) = 6.27$, $p < .05$, $\eta^2 = .73$], and no interaction between those factors [Wilks' Lambda = .591, $F(9,61) = 1.63$, $p > .05$, $\eta^2 = .16$] on the mean speed. Univariate analysis revealed significant effects of joint immobilization on the mean speed of the COP [$F(3,27) = 10.4$, $p < .005$, $\eta^2 = .51$], rambling [$F(3,27) = 14.6$, $p < .001$, $\eta^2 = .43$], and trembling [$F(3,27) = 7.1$, $p < .05$, $\eta^2 = .54$] displacements. Post hoc tests revealed that the mean speed of the COP and the rambling and trembling displacements were smaller in the CH and CT than in the NC condition. Regarding vision, results revealed that the mean speed of the COP [$F(1,9) = 24$, $p < .005$, $\eta^2 = .73$], rambling [$F(1,9) = 16$, $p < .005$, $\eta^2 = .64$], and trembling [$F(1,9) = 11$, $p < .01$, $\eta^2 = .55$] displacements were larger in the CE than in the OE condition.

4. Discussion

As expected, the results of the study, as summarized in Table 2, showed that postural sway was affected by the absence of visual information as well as joint immobilization. In addition, the presence or absence of visual information affected postural sway at each level of joint immobilization in a similar fashion. Overall, independent of COP direction (AP or ML), the rambling and trembling displacements were larger and quicker when participants kept their eyes closed as compared to eyes open. The results further showed that joint immobilization affects postural sway differently in the AP and ML directions. In the AP direction, COP and trembling displacements and speeds were larger than in the control condition (NC) only when the knees, hips, and trunk were immobilized (CT). In contrast, in the ML direction, the COP, rambling, and trembling displacements and speeds dramatically reduced after immobilization of the hip joints (CH and CT conditions). Due to the distinctive effect of joint immobilization in AP and ML directions, the results for each direction will be discussed separately.

4.1. Anterior–posterior direction

The available literature data on the control of the body sway in the anterior–posterior direction are controversial. On the one hand, the results of some studies have indicated that the body sway is controlled mainly at the ankle joints without any significant participation of other joints or muscle groups (Gage et al., 2004; Gatev et al., 1999; Karlsson & Persson, 1997; Winter et al., 1998). By considering the body above the ankles as a rigid structure, such studies have proposed the inverted pendulum model for describing postural control during quiet standing. On the other hand, other studies have claimed that body sway is controlled by compensatory movements from several joints and not a single joint

Table 2
Summary of the effects of joint immobilization on standing balance.

Variables	Immobilization level	AP			ML		
		COP	Ramb.	Tremb.	COP	Ramb.	Tremb.
RMS	CK	=	=	=	=	=	=
	CH	=	=	=	↓	↓	↓
	CT	=	=	↑	↓	↓	↓
Mean speed	CK	=	=	=	=	=	=
	CH	=	=	=	↓	↓	↓
	CT	↑	=	↑	↓	↓	↓

Sign ↑ indicates that a given variable increased statistically significantly as compared with the condition without joint immobilization and open eyes (NCOE); sign ↓ indicates that the given variable decreased; sign = signifies no effect of joint immobilization.

(Krishnamoorthy et al., 2005; Peterka, 2003). According to this view, all joints co-vary, that is, act as a synergy, trying to control the COM displacement (Alexandrov et al., 2001; Creath et al., 2005; Fitzpatrick et al., 1994; Freitas et al., 2006), and minimize the overall joint variance (Krishnamoorthy et al., 2005), which consequently could reduce the muscle activity in a specific joint (for example, the ankle joint) (Kuo & Zajac, 1993). Thus, if this is the case, it could be expected an increase in postural sway when one or more joints were immobilized.

The results of the present study revealed that only after immobilization of the knees, hips, and trunk a small but significant increase in postural sway in AP direction could be identified. These results lead us to refute the hypothesis that postural stability in AP direction can be achieved without significant motion of joints above the ankles and to question the idea that the single inverted pendulum model can adequately describe the upright posture during unperturbed quiet standing in terms of its whole-body sway. These results are in accordance with the results of Fitzpatrick et al. (1994) who reported a 52% increase in body sway (i.e., ankle joint sway) when participants were splinted to limit the sway to the ankles than when the participants stood freely. These authors suggested that, when all body segments are free to move, there is an increase in body stability and that the movements around the ankle joints are not the most determinant factor in body stability.

It is important to mention that in the current study, unlike that of Fitzpatrick et al. (1994), we did not observe any change in RMS of the postural sway variable (i.e., COP). Whereas Fitzpatrick et al. (1994) assessed the RMS of the ankle angle sway (in radians) we assessed the RMS of the COP displacement (cm) in AP direction. However, the different variables have to be linked in the condition when all joints above the ankle are constrained. Therefore, a possible explanation for this discrepancy in results is that Fitzpatrick et al. (1994) immobilized the upper trunk, arms, and head while we kept them unconstrained. Although the upper trunk, arms, and head only make a small contribution to the global COM/COP position, the obviation of head–trunk relative motion rather than lower limbs joint immobilization might have contributed to the increase in body sway. However, this is something yet to be investigated. Clearly, such lack of effect of joint mobilization is only possible in a quiet standing task, where the task offers no or little challenge to healthy individuals. It is well known that in a situation where the individual is perturbed during standing, stereotypical movements across all joints are usually observed (Nashner, Woollacott, & Tuma, 1979).

The observed effect of immobilization on COP speed still leads us to believe that increased body stability is achieved when more joints are free to move. One explanation is that joints' immobilization would increase the level of activation of muscle groups located around the ankle joints which, consequently, could increase the stiffness around the ankles and prevent increase in postural sway. The increase in RMS and mean speed of the trembling trajectories supports the idea that the trembling may be a result of the action of spinal reflexes and changes in the intrinsic mechanical properties of the muscles. However, we were not able to measure muscle activity and, then, more studies are necessary to support this hypothesis.

4.2. Medial–lateral direction

One of the goals of this study was to identify the effects of joint immobilization on medial–lateral (ML) direction. The results surprisingly revealed a reduction of RMS and speed of the COP and the rambling and trembling displacements in ML direction when knee and hips and knee, hips, and lower and middle trunk joints were immobilized. According to Winter and collaborators (Winter, Prince, Stergiou, & Powell, 1993) in the ML direction the magnitude of body sway is constrained at the hip joints as a result of the activation of hip adductors and abductors. Therefore, one would expect that the immobilization of the knee joint would not affect the postural sway in the ML direction because most muscle groups around the knee are related to motions in the anterior–posterior direction. On the other hand, the immobilization of knee and hips and knee, hips, and trunk would cause an increase in postural sway in ML direction, due the fact that the ankle invertors and evertors alone would not be able to restrict sufficiently the COP displacement. In contrast to our expectations, we observed the opposite effect, i.e., a decrease in COP, rambling, and trembling RMS and speed during the immobilization of knees and hips and knees, hips, and trunk. Carpenter and collaborators (Carpenter, Frank, & Silcher, 1999; Carpenter, Frank, Silcher, & Peysar, 2001) verified that when people maintained their upright stance in a threatening situation they decreased displacement amplitude and increased mean frequency due to augmentation of the stiffness caused by increased muscle co-contraction. However, our result cannot be explained by the increased joint stiffness at the ankle joints, for instance by co-contraction of the ankle joint muscles, and, consequently, reduced postural sway due to the fact that postural sway speed also decreased.

A possible explanation for the decrease in sway in the ML direction after joint immobilization would be that, with constrained hip movements, the individuals were less likely to use the mentioned load/unload mechanism resulting in a smaller COP displacement in the ML direction. This would be possible only if the displacement observed in the ML direction was not due to internally generated perturbations itself but due to self-motion and that we are also able to control our quiet standing posture in the ML direction without the use of the load/unload mechanism. The idea of self-motion to explain part of the body sway during quiet standing has indeed been proposed before as a possible exploratory mechanism (Riley, Wong, Mitra, & Turvey, 1997). In addition, it might be possible that the load/unload mechanism using the hip joints is not an exclusive requirement for posture control in the ML direction during quiet standing, but only one of the strategies repertoire [e.g., the ankle eversion/inversion muscles can also participate in the control of standing]. The load/unload mechanism using the hip joints has been shown to be essential for posture control in more challenging tasks involving weight transfers, such as gait initiation, walking, unconstrained standing, among others (Winter et al., 1993, 1996). In this last view, clearly less sway would not mean better control, only that a different mechanism of control is being used during quiet standing.

Another related interpretation for the contrasting effects of joint immobilization on the sway in the AP and ML directions allow for the following hypothesis. The ankle, knee, and hip joints show higher kinematic mobility in the AP direction resulting in a kinematically redundant system able to stabilize the COM location by co-varied changes in these joint angles (Freitas et al., 2006). Motor redundancy may be viewed as an useful feature that allows, in particular, to deal with secondary tasks and external perturbations (Latash, Scholz, & Schöner, 2007; Zhang, Scholz, Zatsiorsky, & Latash, 2008). Joint fixation may be viewed as an example of such a perturbation. Apparently, the kinematic redundancy of the postural chain allowed to keep the AP sway characteristics unchanged under joint immobilization. In contrast, there is limited joint mobility in the ML direction and, as such, the system may be viewed as less (or even non-) redundant. For such a system, any additional constraint may lead to an impossibility of using the earlier mode of control. Note that, although our manipulations were designed to lead to joint immobilization primarily in the AP direction, they likely limited joint mobility in the ML direction as well, partly by limiting muscle length changes for postural muscles with the lines of action in-between the AP and ML axes. If we assume that sway magnitude is to a large degree defined by a purposeful neural process [for example, as a possible exploratory mechanism (Riley et al., 1997)], this process may be suppressed if the controller is impaired in postural control. For example, patients with Parkinson's disease can demonstrate decreased postural sway while postural instability is one of the cardinal features of this disorder (Romero & Stelmach, 2003).

Both interpretations given above consider, in a different degree, that the observed drop in the ML sway is a reflection of a purposeful strategy of the controller that suppresses the natural sway process that may by itself lead to loss of balance under the additional constraints. In addition, the results of the present study corroborate the idea that the control of the body sway in both AP and ML directions during unperturbed upright stance is achieved by two distinct neuromuscular mechanisms that can be influenced by the outcome of each other's action.

In summary, the findings of this study indicate that the single inverted pendulum model is unable to completely explain the processes involved in the control of the quiet upright stance in the anterior–posterior and medial–lateral directions.

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