RESEARCH ARTICLE

Effects of body turn on postural sway during symmetrical and asymmetrical standing

V. L. Talis[1] · O. V. Kazennikov[1]

Abstract

Body sway has usually been studied during symmetrical standing while lower limbs equally contributed in upright posture. The present study aimed to examine the dynamics of body sway while turning during standing with symmetrical and asymmetrical weight distribution between the legs. Subjects performed a body turn of 30° to the right and left during quiet standing and standing with the right or left foot loaded with 70% of body weight. We found that body turn in the symmetrical posture induced weight increase on the foot contralateral to the turning direction and the common center of pressure (COP) velocity increase. Body turn in the asymmetrical posture induced further loading of the foot that was initially overloaded; also turning in the direction of the unloaded foot affects weight distribution more than turning in the direction of the overloaded foot. The posture transition from symmetrical to asymmetrical induced the common COP velocity increase and forward protraction of the unloaded foot COP. Turning in the asymmetrical posture produced further increase of the common COP velocity and further forward protraction of the unloaded foot COP. Moreover, when the left leg was unloaded this resulted not only in left leg's COP forward, but also in left leg's COP lateral protraction, and left leg's COP frontal velocity increase. These findings reveal that body position and weight distribution between the feet interact to stabilize upright posture and show the effect of footedness during turning in asymmetrical standing.

Keywords Upright standing · Turning · Asymmetrical posture · Center of pressure · Postural sway · Lateralization · Human

Introduction

Neuromuscular control of standing aims to prevent fall and keeps the trajectory of the common center of pressure (COP) inside the feet support area. Kinematical analysis of the upright standing showed that joint angles co-varied to keep the trunk orientation relatively unchanged (Alexandrov et al. 1998; Latash 2008). Findings for sagittal plane dynamics of ordinary standing have shown that the trajectory of the common COP could be considered as a superposition of the migration of the reference point (rambling) and the deviation away from that point (trembling) (Zatsiorsky and Duarte 1999, 2000). Maintenance of upright stance has usually been investigated in ordinary, symmetrical standing (Gurfinkel and Osovets 1972; Nashner and McCollum 1985;

Massion 1992). Since the major body segments have larger amplitude of motion in the sagittal plane during upright balancing, the question arose of what would be the postural sway if body rotated to the side, and therefore appeared not parallel but turned relative to the lower segment's plane? The role of proprioception of upper body in the regulation of whole-body position has been intensively investigated, using vibration to stimulate the muscles of the upper part of the body. It has been shown that a postural shift of the whole body occurs contra-laterally to the side of the neck where the stimulation was applied (Roll and Roll 1988). In addition, the extent of the postural shift during vibration of the neck muscles depended on the instability of the posture (Ivanenko et al. 1999).The influence of upper body proprioception on upright standing regulation was also investigated in clinical study. It was shown that conventional orthopaedic treatments could not significantly improve balance control in adolescent idiopathic scoliosis patients since scoliosis development affects upper body proprioception (Pialasse and Simoneau 2014).

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During everyday activity, humans often stand asymmetrically, when one leg is loaded more than another. It is well documented that standing with unequal weight distribution between legs could be a sign of tiredness (Vuillerme and Boisgontier 2010), age (Blaszczyk et al. 2000), orthopedic and neurological disease (Talis et al. 2008; Genthon et al. 2008), as also a preparation for upcoming motion such as, for example, turning (Hase and Stein 1999; Solomon et al. 2006). Recent experiments on standing with asymmetrical weight bearing between feet have shown that the velocity of the overloaded leg's COP increased in the anterior–posterior (AP) direction, but did not change in the medio-lateral (ML) direction and the velocity of the unloaded leg's COP motion increased in the ML direction (Wang and Newell 2012; Kazennikov et al. 2013). It was suggested that in asymmetrical standing the involvement of a leg in maintaining vertical posture depends on the load that is distributed upon this leg.

In the current study, we investigated body turn in symmetrical and asymmetrical posture. To our knowledge, only few studies on kinematics and dynamics of body turn exist (Hase and Stein 1999; Solomon et al. 2006; Wada et al. 2014; Sung 2014; Robins and Hollands 2017). In the paper by Solomon et al. (2006), it was shown that subjects first lift the foot ipsilateral to the turning direction, while maintaining stance on the opposite foot during step turn. Based on this, we supposed that upper body turning could be accompanied by overloading of the leg contralateral to the turning direction. Moreover, considering the asymmetrical posture to be a preparation for turning into the corresponding direction, we supposed that upper body turn would significantly depend on weight distribution between feet.

Even though there is no single accepted definition of footedness, growing experimental data have shown a functional difference of the feet in asymmetrical stance (Stea et al. 2008; Kinsella-Shaw et al. 2013; Wang and Newell 2013). Based on a recent investigation by Wang and Newell (2013) showing the stabilizing and mobilizing feet functional difference in asymmetrical stance, we also supposed that the effect of body turn on balance in symmetrical and asymmetrical standing could be different during standing with the right or left leg overloaded and during turning in the right and left direction, thus highlighting the notion of limb dominance.

Methods

Participants

Fourteen healthy right-leg dominant subjects participated in the study (five females and nine males; mean age 27.1 ± 14.01 SD; weight 65.8 ± 16.4 kg; height 168.5 ± 7.4 cm). The dominant leg was identified by

Waterloo Footedness Questionnaire-Revised (WFG-R) (Elias et al. 1998), as a leg used for kicking a ball, stepping up stairs and stepping on an object. The procedures were approved by the Institute for Information Transmission Problems Ethics Committee and conformed to the Declaration of Helsinki. Each individual was informed of the study procedures before their consent to participate in the study.

Procedure

During the experiment, the subjects stood barefoot with eyes closed with one foot on one of the two adjacent stabilographs "Stabilan 01-13" (OKB Ritm, Russia, sampling frequency − 50 Hz). The subjects were asked to place feet side-by-side in such a manner that their feet were externally rotated at 30° and with their heels at 10 cm apart (there were marks drawn on the force plates). In the first trial, subjects were instructed to stand for 120 s: 30 s—symmetrically, 30 s—during turning right, 30 s—symmetrically and 30 s—during turning left. The order of right and left turn was randomized within subjects. In the second and third trail, the same protocol was executed in two asymmetrical postures—right or left foot overloading, which order was also randomized between subjects. Turning was stopped at the verbal command of the experimenter, when the angle of the pointer mounted on the head of the subject reached 30° from the center in correspondence with the mark on the wall. 30° amplitude of turning was chosen to avoid large disturbance in standing and feet position change [kinematical data of step turn of standing subject presented in the paper by Solomon et al. (2006) have shown that the initial part of body turn (up to 30° of head motion to the side) is accompanied by pelvis rotation only without feet position change]. It was emphasized that the subject should move the upper body, not just turn the head to the side. Before the experimental trials, all subjects were familiarized with the protocol and practiced turning and transferring the load onto one or the other leg under visual control on a stabilograph connected PC screen to keep not more than 70% of weight on the overloaded leg. During the experiment, the subject overloaded one leg under the verbal control of the experimenter. The total duration of the whole experiment was about 15 min and it was executed in 1 day.

Data processing

The asymmetry index was calculated through the following equation (Talis et al. 2008): $AsI = ((R_L - R_R)/(R_L + R_R)) \times 100\%$, where R_L and R_R are the mean vertical reaction forces under the left and right foot. The common COP motions were calculated for movements projected along the ML and AP axes from the plantar center of pressure trajectories measured under each separate foot (COP_L

and COP_R), weighted by R_L and R_R through the following equation (Winter et al. 1996):

$$COP = COP_L \times R_L/(R_L + R_R) + COP_R \times R_R/(R_L + R_R).$$

The mean position and velocity of the common COP, COP_L and COP_R along the AP and ML directions were calculated by the MATLAB programming environment. The mean value of the common COP, COP_L and COP_R was computed during 20 s of standing in each position (the transitional period, that was less than 10 s was extracted from the analysis). The slow drift of the common COP, COP_L and COP_R was removed from row recording data by the Butterworth fourth-order high-pass filter (cutoff 0.1 Hz) for the calculation of the velocities.

Statistical analysis

The statistical package Statistica was used for all statistical procedures. One-way ANOVA was performed on AsI and the common COP mean position in the ML direction as dependent variables with Turn (straight, turn right, turn left) as a factor for symmetrical and two asymmetrical standing. 3×3 ANOVA was performed on the common COP mean position in the AP direction, and also on COP_R and COP_L, mean positions and velocities in the AP and ML directions with Load (symmetrical load, right leg overloading, left leg overloading) and Turn (straight, turn right, turn left) as factors. Pairwise contrasts with Bonferroni corrections were carried out to discern differences identified by the ANOVAs unless otherwise stated. All mean values are presented with standard errors. Statistical significance was set at $P < 0.05$. The coefficients of correlation between the loaded leg's COP mean velocity and the common COP mean velocity in the AP and ML directions were also calculated.

Results

Common COP, COP_R and COP_L mean position

Individual data (Fig. 1) and data averaged across all subjects (Fig. 2) data on COP_L, common COP and COP_R are shown during standing symmetrically (in a square), standing with right foot overloaded (outlined by a solid line) and left foot overloaded (outlined by a dashed line). One can see that the common COP migrates to the loaded side during one leg overloading and further continues its motion laterally due to any turn (Fig. 2b). ANOVA confirmed main effect of Turn on the ML location of the common COP during left leg overloading ($F_{(2, 26)} = 6.53$, $P < 0.01$). At the same time, COP of the overloaded foot moved backward (dashed line oval on Fig. 1a and solid line oval on Fig. 1c) and COP of the unloaded foot moved forward (solid line oval on Fig. 1a and dashed line oval on Fig. 1c). The effect of Load ($F_{(2, 26)} = 18.87$, $P < 0.00005$) on COP_R and COP_L ($F_{(2, 26)} = 28.89$, $P < 0.00001$) was confirmed in ANOVA. Additionally, there was significant interaction Load×Turn ($F_{(4, 52)} = 3.06$, $P < 0.05$) for COP_R and COP_L ($F_{(4, 52)} = 3.2$, $P < 0.05$). Pairwise contrasts revealed that COP of unloaded foot moved forward ($P < 0.05$) and continued its forward motion during any turn ($P < 0.05$). In the ML direction, there were larger lateral migrations of COP_L than those of COP_R (compare solid line oval on Fig. 1a and dashed line oval on Fig. 1c). ANOVA for COP_L position in the ML direction showed main effect of Load ($F_{(2, 26)} = 33.14$, $P < 0.00001$) and Turn ($F_{(2, 26)} = 12.65$, $P < 0.0005$). Pairwise contrasts revealed that COP_L shifted laterally during unloading ($P < 0.05$) and turn right induced its further lateral migration ($P < 0.05$) (solid line oval on Fig. 2a).
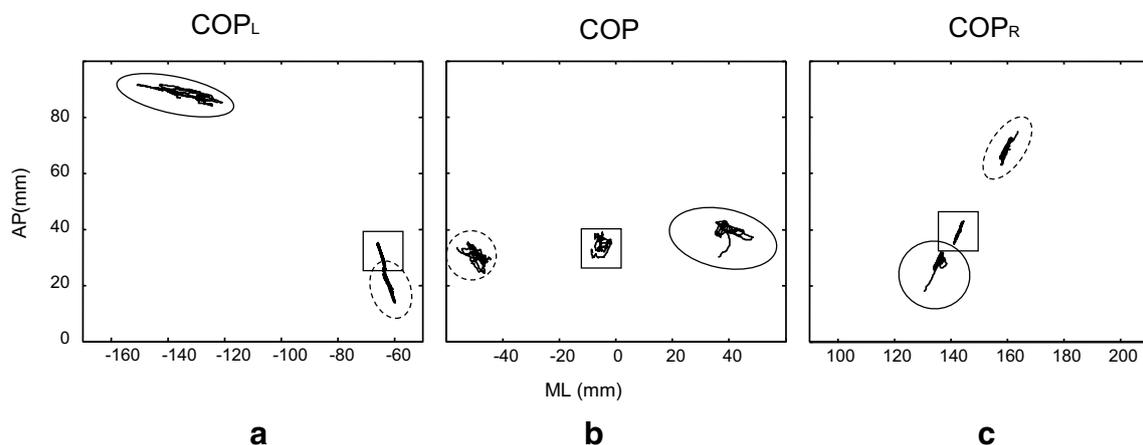

Fig. 1 Example of the trajectories of the common COP (**b**), COP_L (**a**) and COP_R (**c**) for one representative subject standing symmetrically (square) and while overloading the right foot (solid line oval) or left foot (dashed line oval)
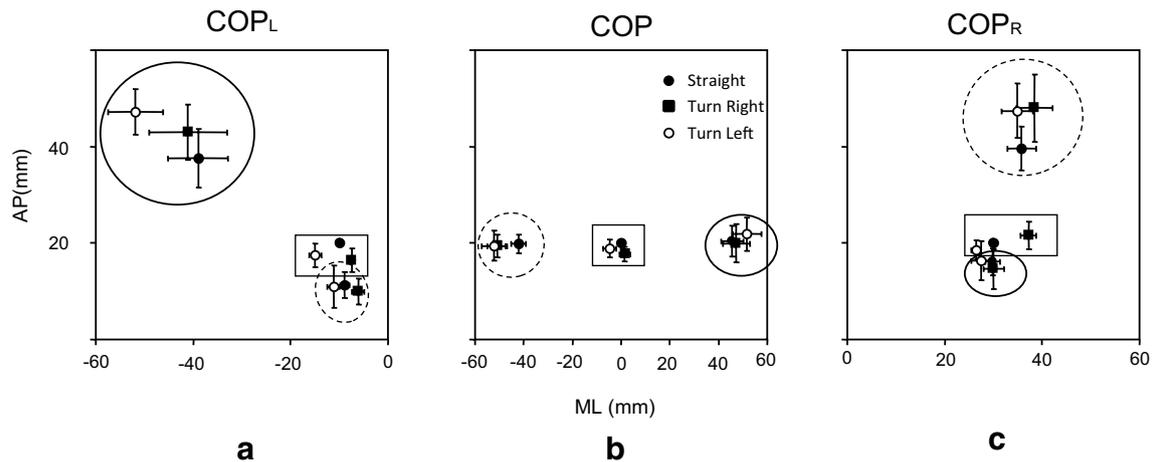
Fig. 2 Mean position of the common COP (**b**), COP$_L$ (**a**) and COP$_R$ (**c**) during standing symmetrically (square) and while overloading the right foot (solid line oval) or left foot (dashed line oval). The val-

ues are presented relative to those during ordinary standing for each individual subject. Note the ML scale difference on **b**. Data averaged across subjects with standard error bars are shown

Fig. 3 Asymmetry index, AsI as a function of upper body position and weight distribution (**a** symmetrical standing, **b** standing with right foot overloading, **c** standing with left foot overloading). The post hoc effects when statistically significant are indicated by horizontal braces ($P < 0.05$). Data averaged across subjects with standard error bars are shown
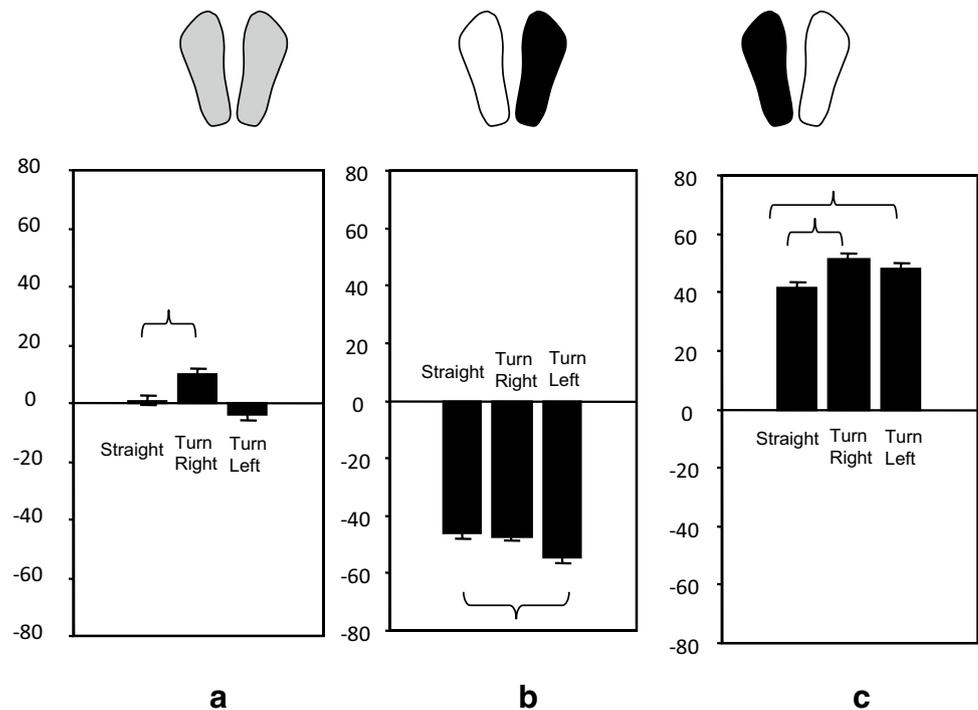
Weight distribution

AsI, averaged across all subjects and conditions asymmetry index, is shown in Fig. 3. One can see that turning in symmetrical posture induced load increase on the contralateral foot (Fig. 3a). There was a significant main effect of Turn ($F_{(2, 26)} = 16.58$, $P < 0.00005$) on AsI and pairwise comparisons indicated a significant increase in AsI during turn right ($P < 0.005$) and the tendency of AsI increase during turn left ($P = 0.1$). In asymmetrical standing with the right leg overloaded (Fig. 3b), there was the

main effect of Turn ($F_{(2, 26)} = 5.45$, $P < 0.05$) on AsI and pairwise contrasts revealed a significant increase in AsI during turn left ($P < 0.05$). In asymmetrical standing with left leg overloaded (Fig. 3c), there was a main effect of Turn ($F_{(2, 26)} = 9.45$, $P < 0.001$) and pairwise contrasts revealed a significant increase in AsI during turn right ($P < 0.001$) and left ($P < 0.05$). Thus, in asymmetrical standing any turning induced weight increase on the overloaded leg and also turning in the direction of the unloaded leg has greater impact.

Common COP, COP$_R$ and COP$_L$ mean velocities

Averaged across all subjects and conditions, mean velocities of the common COP, COP$_R$ and COP$_L$ are shown in Fig. 4. One can see that transition into asymmetrical standing induced an increase in the common COP velocity and further turning produced its further increase in the AP and ML directions (Fig. 4a, d). The effect of Load ($F_{(2, 26)} = 5.76$, $P < 0.01$) and Turn ($F_{(2, 26)} = 9.5581$, $P < 0.001$) was confirmed in ANOVA for the common COP velocity in the AP direction, and also in the ML direction [Load ($F_{(2, 26)} = 5.24$, $P < 0.05$), Turn ($F_{(2, 26)} = 8.15$, $P < 0.005$)].

At the same time, the velocity of COP$_R$ increased in the AP direction (Fig. 4b) due to transition into any asymmetrical posture and increased further due to any turn. ANOVA confirmed the main effect of both factors on the AP velocity of COP$_R$ [Load $F_{(2, 26)} = 3.84$, $P < 0.05$, Turn $F_{(2, 26)} = 5.44$, $P < 0.05$]. In the ML direction, the main

effect of turn on the COP$_R$ velocity was also significant ($F_{(2, 26)} = 9.67$, $P < 0.001$) and pairwise contrasts revealed its increase due to any turn to the right—even the right foot was loaded or unloaded ($P < 0.05$) (Fig. 4e).

Figure 4c shows that the ML velocity of COP$_L$ increased significantly due to unloading. ANOVA confirms the effect of Load ($F_{(2, 26)} = 35.609$, $P < 0.00001$). ANOVA for the AP velocity of COP$_L$ showed the main effect of Turn ($F_{(2, 26)} = 4.26$, $P < 0.05$). Pairwise contrasts revealed that the AP velocity of COP$_L$ increased due to any turn during standing with left leg overloading in comparison with that in ordinary standing ($P < 0.05$) (Fig. 4c).

High correlation was found between velocities of the loaded foot's COP and the common COP in the AP direction (0.97 and 0.93 for right and left foot overloaded, correspondingly). The correlation between the velocities of the loaded foot's COP and the common COP in the ML direction was low (0.23 and 0.24 for right and left overloaded, correspondingly).
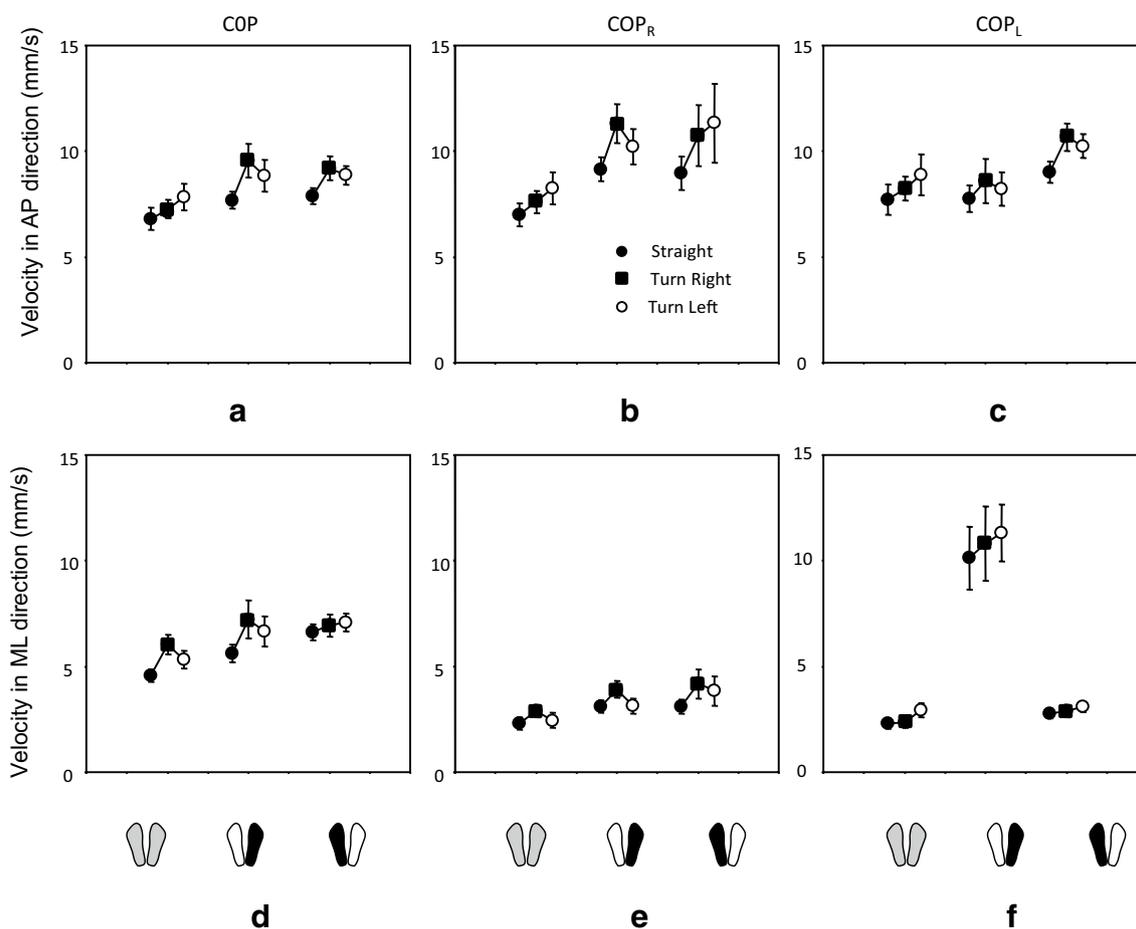

Fig. 4 Mean velocity in the AP and ML directions for the common COP (**a**, **d**), COP$_R$ (**b**, **e**) and COP$_L$ (**c**, **f**) as a function of upper body position and weight distribution. Symbols of weight distribution are similar to Fig. 3. Data averaged across subjects with standard error bars are shown

Discussion

The purpose of this study was to examine how the two mechanical factors—body turn and weight distribution—interact to influence postural regulation. Based on data about step turn (Solomon et al. 2006), we supposed that turning in symmetrical posture would be accompanied by overloading the leg contralateral to the turning direction. Consequently, we expected that turning being executed in asymmetrical posture would significantly depend on turning direction. In compliance with our first prediction, we found that body turn induced load increase on the foot contralateral to turning direction during symmetrical standing similarly to step turn (Fig. 3a). The same turn executed in asymmetrical standing produced further overloading of the initially loaded foot, but turning into direction of the unloaded foot induced larger overloading than turning into the direction of the loaded foot, thus confirming our second prediction (Fig. 3b, c). Our findings on feet center of pressure location in asymmetrical standing (Fig. 1) are comparable with results of Kazennikov et al. (2013) and Wang and Newell (2012), which show forward motion of the unloaded foot COP and backward motion of the loaded foot COP. Our new data are that turning in asymmetrical posture resulted in further separation of feet COP mean position, aimed to stabilize already unstable asymmetrical posture (Fig. 2). Thus, asymmetrical standing appeared to elucidate the effect of body turn during symmetrical standing—that is when the COP of the loaded foot moves closer to the heel of the foot to prevent the body from falling backwards. This result was stressed by the fact that in asymmetrical standing the loaded foot COP moved backward and the unloaded foot COP moved forward, thus resembling the situation where subjects were instructed to load the feet evenly in a tandem position, but in fact they loaded 60% of their body weight on their rear foot (Jonsson et al. 2005). Partial transition of body weight on one of the feet brings about a difference mobility of loaded and unloaded leg thus changing the inter-coordination of hip and ankle joint (Gunther et al. 2008). Body turn induced further asymmetry in axial muscles due to the non-rigid link between body sides (Dos Anjos et al. 2018) that highlights itself in the progressive increase of body sway in this posture (Fig. 4).

Our findings are consistent with previous studies (Kinsella-Shaw et al. 2013; Wang and Newell 2013) that have shown that lateralization of legs and trunk is not detectable in quiet standing in the absence of imposed asymmetries. In our present study, footedness effect appeared across all conditions: it is highlighted as larger leg overloading during turning to the dominant side in symmetrical standing (Fig. 3a); in asymmetrical standing it was shown as the larger lateral shift of the unloaded non-dominant leg,

than those of the dominant leg (Fig. 2a versus c), larger frontal oscillation of the unloaded non-dominant leg than those of the dominant leg (Fig. 4f versus e), also dominant leg exhibited similar velocity increase due to loading and unloading (Fig. 4b, e) in contrast to non-dominant leg. Moreover, even posture transition from the symmetrical to asymmetrical one induced the common COP velocity increase in both directions, left leg overloading induced larger increase of ML velocity than right leg overloading (Fig. 4d). The significant footedness effect found in our data on body turn could be due to the fact that trunk muscles connected to the arms are involved in weight transition to the side less in asymmetrical standing than in body turn and consequently body turn is more side dependent than asymmetrical standing (Sung et al. 2004).

There were several limitations to this study. First, there is the selection of right-footed individuals. It would be necessary to conduct further studies with the same group of left-footed individuals to generalize the results with right-dominant and left-dominant subjects. Secondly, there is the consideration that two instructions in parallel (to keep more weight on one foot and also turning in both side in this position) might mentally overload our subjects, but at the same time a large number of significant data obtained in our present research show that our subjects understood the instructions identically and were able to explore it identically. Thirdly, the kinematic data could support our COP analysis for comprehensive understanding of the dynamic results obtained by the stabilograph.

The note of Solomon et al. (2006), that "turns are a relatively neglected area of study, despite being a ubiquitous behavior in daily activities and a significant source of difficulty in patients with balance disorders", remains true in more than 10 years later. Since that time several research studies devoted to the interrelation of shoulder and pelvis in healthy and patients with low back pain studied, as a rule, large body turn to one side [as for instance turning left in the paper by Sung (2014)]. In the present paper, we have analyzed a small body turn that appeared to have an effect on weight distribution between the feet and therefore on posture control—far from the stability limit. These small body turns with another postural task added, that is, asymmetrical standing, allowed us also to see the dominant side preference in postural control.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Alexandrov A, Frolov A, Massion J (1998) Axial synergies during human upper trunk bending. Exp Brain Res 118:210–220

Blaszczyk JW, Prince F, Raiche M, Hebert R (2000) Effect of ageing and vision on limb load asymmetry during quit stance. J Biomech 33:1242–1248

Dos Anjos FV, Gazzoni M, Vieira TM (2018) Does the activity of ankle plantar flexor differ between limbs while healthy, young subjects stand at easy? J Biomech 81:140–144

Elias LJ, Bryden MP, Bulman-Fleming MB (1998) Footedness is a better predictor than is handedness of emotional lateralization. Neuropsychologia 36:37–43

Genthon N, Rougier P, Gissot AS, Froger J, Pélissier J, Pérennou D (2008) Contribution of each lower limb to upright standing in stroke patients. Stroke 39:1793–1799

Gunther M, Otto D, Muller O, Blickhan R (2008) Transverse pelvic rotation during quit human stance. Gait&Posture 27:361–367

Gurfinkel VS, Osovets SM (1972) Dynamics of equilibrium of the vertical posture in man. Biofizika 17:478–485 **(in Russian)**

Hase K, Stein RB (1999) Turning strategies during human walking. J Neurophysiol 81:2914–2922

Ivanenko YuP, Talis VL, Kazennikov OV (1999) Support stability influences postural responses to muscle vibration in humans. Eur J Neurosci 11:647–654

Jonsson F, Seiger A, Hirschfeld H (2005) Postural steadiness and weight distribution during tandem stance in healthy young and elderly adults. Clin Biomech 20:202–208

Kazennikov OV, Kireeva TB, Shlykov VYu (2013) Characteristics of vertical posture maintenance during standing with asymmetrical loading. Hum Physiol 39:392–399

Kinsella-Shaw JM, Harrison SJ, Carello C, Turvey MT (2013) Laterality of quit standing in old and young. Exp Brain Res 231:383–396

Latash ML (2008) Synergy. Oxford University Press, Oxford

Massion J (1992) Movement, posture and equilibrium interaction and coordination. Prog Neurobiol 38:35–56

Nashner LM, McCollum G (1985) The organization of human postural movements: a formal basis and experimental synthesis. Behav Brain Sci 8:135–172

Pialasse JP, Simoneau M (2014) Effect of bracing or surgical treatments on balance control in idiopathic scoliosis: three case studies. J Can Chiropr Assoc 58(2):131–140

Robins RK, Hollands MA (2017) The effects of constraining vision and eye movements on whole-body coordination during standing turns. Exp Brain Res 235:3592–3603

Roll JP, Roll R (1988) From eye to foot. A proprioceptive chain involved in postural control. In: Ambland B, Berthoz A, Clarac F (eds) Posture and gait: development, adaptation, modulation. Elsevier, Amsterdam, pp 155–164

Solomon D, Kumar V, Jenkins A, Jewell J (2006) Head control strategies during whole-body turns. Exp Brain Res 173:475–486

Stea S, Bordini B, Viceconti M, Traina F, Cervini A, Toni A (2008) Is laterality associated with a higher rate of hip arthroplasty on the dominant side? Artif Organs 32:73–77

Sung PS (2014) A kinematic analysis for shoulder and pelvis coordination during axial trunk rotation in subjects with and without recurrent low back pain. Gait Posture 40:493–498

Sung PS, Spratt KF, Wilder DG (2004) A possible methodological flaw in comparing dominant and non dominant sided lumbar spine muscle responses without simultaneously considering hand dominance. Spine 29:1914–1922

Talis VL, Grishin AA, Solopova IA, Oskanyan TL, Belenky VE, Ivanenko YP (2008) Asymmetric leg loading during sit-to-stand, walking and quit standing in patients after unilateral total hip replacement surgery. Clin Biomech (Bristol, Avon) 23:424–433

Vuillerme N, Boisgontier M (2010) Changes in the relative contribution of each leg to the control of quit two-legged stance following unilateral plantar-flexor muscles fatigue. Eur J Appl Physiol 110:207–213

Wada O, Tateuchi H, Ichihashi N (2014) The correlation between movement of the center of mass and the kinematics of the spine, pelvis, and hip joints during body rotation. Gait Posture 39:60–64

Wang Z, Newell KM (2012) Asymmetry of foot position and weight distribution channels the inter-leg coordination dynamics of standing. Exp Brain Res 222:333–344

Wang Z, Newell KM (2013) Footedness exploited as a function of postural task asymmetry. Laterality 18:303–318

Winter DA, Prince F, Frank JS, Powell C, Zabjek KF (1996) Unified theory regarding A/P and M/L balance in quit standing. J Neurophysiol 75:2334–2343

Zatsiorsky VM, Duarte M (1999) Instant equilibrium point and its migration in standing tasks: rambling and trembling components of the stabilogram. Mot Control 3:28–38

Zatsiorsky VM, Duarte M (2000) Rumbling and trembling in quit standing. Mot Control 5:185–200

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