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ORIGINAL ARTICLE

Postural instability and position of the center of pressure into the base of support in postmenopausal osteoporotic and nonosteoporotic women with and without hyperkyphosis

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Abstract

Summary In postmenopausal women, thoracic hyperkyphosis affects postural instability in the sagittal plane, whereas osteoporosis affects it in the frontal plane. Decrease of hip muscle strength can be changed the center of pressure distance to the center of base of support. These results may be important to design the therapeutic exercise for decreasing the postural instability.

Purpose In this study, we investigated the effect of bone mineral density (BMD) and thoracic kyphosis on the center of pressure (CoP) sway and its location related to the base of support (BoS).

Methods Ten young and 39 postmenopausal women voluntarily participated in this study. Postmenopausal women were divided into four groups according to the thoracic kyphosis angle (normal kyphotic $< 50° \leq$ hyperkyphotic) and T-score values. The isometric strength of the trunk and lower limb muscles were measured. The CoP postural sway was measured in a comfortable double stance position, and the location of the CoP was then determined related to the BoS.

Results In both hyperkyphotic groups (osteoporotic and normal BMD), the strength of back extension and hip adduction showed a significant decrease compared to the normal kyphotic groups. In the osteoporotic groups (hyper- and normal kyphotic), hip abduction and ankle plantar flexion were significantly weaker than those in the nonosteoporotic groups. In both hyperkyphotic groups, velocity of the CoP displacement in the anterior-posterior (AP) direction was significantly higher than that in the young group, while, in both of the osteoporotic groups, velocity of the CoP displacement in the medio-lateral (ML) direction was significantly higher than that in the young group. In postmenopausal women, hip extensor strength negatively and significantly correlated with the CoP distance to the center of the BoS.

Conclusion It appears that thoracic hyperkyphosis affects postural instability in the AP direction and that a decrease of BMD affects postural instability in the ML direction.

Keywords Thoracic hyperkyphosis · Osteoporosis · Postmenopausal women · Base of support · Center of pressure

Introduction

After menopause, bone cells are less mechanosensitive due to estrogen deficiency, so that lower or even normal early mechanical loading is insufficient to maintain skeletal bone mass, leading to a net negative bone balance (postmenopausal osteoporosis) [1].

Osteoporosis is actually characterized by bone fragility and micro-architectural deterioration. The conceptual definition of osteoporosis links the high risk of postmenopausal fractures to low bone mineral density (BMD) and qualitative changes in the micro-architecture [2].

The high socio-economic impact of osteoporosis is due to the increased incidence of the disease, mortality, and fracture-related costs. According to a report from the National Health

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and Nutrition Examination Survey (NHANES), osteoporosis affected more than 55.5% of US adults aged ≥ 50 years in 2013–2014 [3], also, each year, 3.1 million osteoporotic fractures occur in Europe [4]. According to the results of a meta-analysis study, the overall prevalence of osteoporosis and osteopenia has been increasing in recent years in the Iranian population, which means that complications such as osteoporotic fractures have also increased. This could represent a critical public health problem in Iran in the near future [5]. Thus, targeting women with increased risk of osteoporotic fracture is an important challenge in the field of osteoporosis. At present, the fracture risk assessment (FRAX) algorithm is used to predict fracture risk through clinical risk factors (CRFs) and BMD. Additionally, it has been proven that the addition of fall risk as an independent risk factor to other CRFs and BMD modestly increases the predictive capacity of such assessment tools [6]. In this context, gait and balance disorders have been identified in multiple reviews as the strongest risk factors for falls and fractures [7, 8].

One commonly used way to evaluate the postural balance of older adults is to measure the excursion of the center of pressure (CoP) with a force platform in quiet standing [8]. The CoP represents weighted average location of the ground reaction forces [9].

A strange consequence of using the CoP excursion as a measure of stability is that a broomstick, which can stand on its end without motion of the CoP or the center of mass (CoM, The CoM is an imaginary point, which the total body mass can be assumed to be concentrated [10]), as an example of perfect balance, is much better than a man standing on both feet [11]. In addition, there are conflicting data about the CoP sway related to postural instability. According to the results of one review, most authors associate postural instability with increases in the CoP amplitude [12]. Others have proposed that the loss of variability may be related more to postural instability [13, 14]. The controversy even extends to the direction of the CoP displacement; some results show that lateral the CoP excursions could provide more information about balance control in the elderly [15, 16]. Other authors have not found age-related differences in the lateral direction, but reported differences in the AP direction [17, 18].

Therefore, it seems that traditional CoP measures might not be sufficient for postural stability assessment in the upright position. Postural control generally defines the body's ability to adjust the CoP in order to maintain projection of the CoM within the manageable limits of the base of support (BoS, during a double-legged stance, the CoP obtained when both feet are in contact with a single force platform, so in this condition, base of support is the area which is surrounded by the outside edge of the feet, in contact with the ground/surface) [19], so we proposed that the CoP position into the BoS could provide more information about the balance strategies used by osteoporotic women. Another aim of this study was related to the independent effects of thoracic hyperkyphosis and BMD on the postural stability parameters in postmenopausal women. Kyphotic posture may cause anterior displacement of the CoM, which increases the risk of falls from postural instability [20].On the other hand, one hypothesis proposed that low BMD may lead to vestibular dysfunction by altering the petrous part of the temporal bone, which is followed by postural instability due to the impairment of the interaction of sensory inputs [21]. It appears that postural stability as a main risk factor for falling may be independently affected by thoracic hyperkyphosis and low BMD. Therefore, the present study was designed to investigate the effects of thoracic hyperkyphosis and osteoporosis on the position of the CoP into the BoS, which may provide more accurate explanations for the cause of postural instability in postmenopausal women. Regarding the positive effect of muscular strength, especially in the trunk and lower limbs, on the balance control of the elderly [22–25], the isometric strength of the trunk and lower limb muscles was also compared among the postmenopausal groups with different BMD and thoracic curve status to investigate the correlation of these variables with CoP-related parameters.

Methods

This is a cross-sectional study conducted at the Gait Analysis Laboratory of the Physical Therapy Department of Tarbiat Modares University, Tehran, Iran. We assessed 62 volunteer postmenopausal women for participation in the study. The inclusion criteria included females 48–75 years of age, menopausal for at least 1 year prior to the study, with no record of regular physical exercise for at least 1 year. The subjects who had secondary osteoporosis, a history of osteoporotic fracture, the presence of neurogenic or myopathic disorders, diabetes, thyroid disease, the use of drugs known to affect muscle strength, rheumatoid diseases, or any type malignant neoplasia were excluded from the study. The Medical Ethics Committee of Tarbiat Modares University approved the study. The methods and the aims of doing assessments were explained completely to all participants, who signed permission forms before the start of assessments. A total of 39 volunteers were enrolled in the study. All the subjects were right handed. They were classified into four groups based on kyphotic angle and osteoporotic status: osteoporotic hyperkyphotic, ($n = 10$), osteoporotic normal kyphotic ($n = 12$), nonosteoporotic normal kyphotic ($n = 10$), nonosteoporotic hyperkyphotic ($n = 7$). Women with a kyphosis angle of more than 50°, lumbar T-score ≤ −2.5, and lumbar T-score > −1 were placed in the hyperkyphotic, osteoporotic, and nonosteoporotic groups, respectively. A group of young healthy women ($n = 10$) 24–30 years of age were also enrolled to compare their CoP parameters with those of the postmenopausal groups.

Measures

All subjects were assessed in two sessions within 24 h. During the first session, anthropometric parameters were recorded, and kyphosis degree and isometric muscular strength were measured. Postural control was assessed in the second session after 24 h in order to eliminate the effects of fatigue.

Age (year), body mass index (BMI, weight/height^2, kg/m^2), menopause duration (year), and length of the dominant leg (cm) were recorded for each participant.

BMD measures

Dual-energy x-ray absorptiometry (DXA, posterior-anterior scan of the lumbar spine, from L1 to L4, hip, and femoral neck), was assessed 3–6 months before the study for all the subjects, willing to participate in this study.

Kyphosis degree

Spinal kyphosis was measured in each subject by 50 cm flexicurve ruler (LinexCo., UK), which can be bent in only one plane and retains the shape into which it is bent. The subject was instructed to stand up straight, and the flexicurve ruler was aligned to the AP curves of the spine from C7 to T12. The ruler was then placed on a paper, and its outline was traced. A straight line was then drawn from the ruler position C7 to ruler position T12, corresponding to the length of thoracic kyphosis (L), which was measured in centimeters. The height of the thoracic kyphosis (H) in centimeters was determined by drawing a perpendicular line from the highest point in the thoracic curve to the point at which it intersected the straight line drawn from C7 to T12 (Fig. 1). The kyphosis degree was calculated by applying the formula: 4[Arc tan(2H/L)] [26].

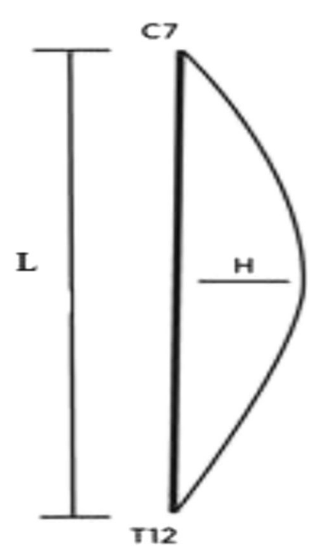

Fig. 1 Schematic drawing for determination of length (L) and height (H) of thoracic kyphosis to calculate kyphosis degree

Muscular strength

The isometric strength of the back extensor muscles, hip abductors, adductors, extensors and flexors, knee extensors and flexors, and dorsi and plantar flexors of the ankle were measured bilaterally. The measurement was done by a digital handheld dynamometer (Hand-held Dynamometer; Lafayette Instrument Co., Lafayette, IN, USA) which can record the muscular strength from 0.2 to 199.9 kg. The measurements were recorded by the Make method because of its repeatability reported of 0.909 [27].

The measurements were recorded in kilograms (kg). Each of the muscular groups was tested three times bilaterally by a single tester, and at least 1 min of rest was allowed between repeated tests of the same muscular group; the mean of these measurements was reported as the strength of that group. The duration of each isometric test was 5 s. The procedure, which included test positions, stabilized regions, and dynamometer placements, was based on Bohannon et al.'s study [28].

Static balance

The static postural balance assessment of all participants was performed on a force plate (9286AB; Kistler Co., Winerthur, Switzerland). For data acquisition, the force plate was connected to a signal-amplifying interface box linked to a computer. The chosen sampling frequency was 100 Hz. Data were analyzed utilizing MATLAB software. All participants were assessed in a comfortable double stance position (selected to assess balance strategies routinely chosen by the women to maintain their CoM in the limits of stability). Data were taken with eyes open; registration time was 20 s. The parameters measured were as follows: mean velocity of the CoP sway and its standard deviation (SD) in the AP and ML directions, distance between mean position of the CoP and the geometric center of the BoS (Dp), ratio of Dp to the area of the BoS (Dp/Ap), and the angle of the mean position of the CoP into the geometric center of the BoS. For investigation of the CoP position into the BoS (Dp, Dp/Ap, angle of the CoP position), a square graph paper was attached to the force plate. The Y-axis (ML direction) is indicated by numbers, and the X-axis (AP direction) is indicated by English alphabet letters (Fig. 2).

Four landmarks (for each foot) were chosen by the custom-designed software to draw the BoS and included: (1) middle point of the posterior of heel, (2) lateral malleolus, (3) head of the fifth metatarsal bone, and (4) tip of the big toe. The landmarks were defined by R1–R4 and L1–L4 (for right and left sides, respectively) (Fig. 2).

The participant was instructed not to change the position of her feet position, and the CoP sway was registered. Subsequently, to obtain the BoS, the coordinates of the landmarks were entered into software developed in MATLAB, and the Dp, Dp/Ap, and angle of the CoP position were determined (Fig. 2).

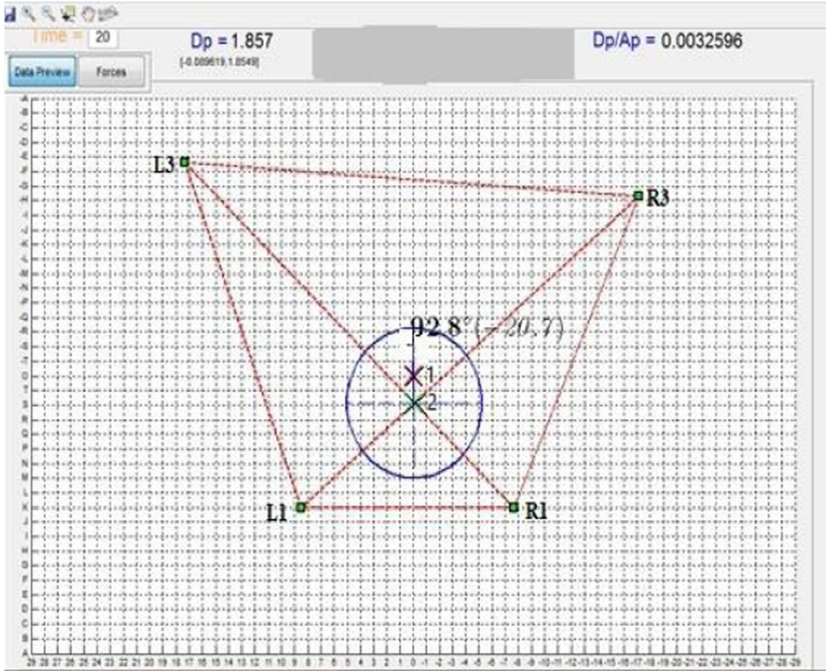

Fig. 2 Drawing of the BoS and mean position of the CoP by software developed utilizing MATLAB. X1 Marker: Mean position of the CoP sway X2 Marker: Geometric center of the BoS Circle: Trigonometric circle drawn relative to the geometric center of BoS with a constant radius to assess the angle of CoP position Dp: Distance between mean position of the CoP and the geometric center of the BoS (distance between X1 and X2 marker) Dp/AP: Ratio of Dp to the area of the BoS, BoS: The area of trapezoid Trapezoid: The area of both feet drawn base on four L1, L3, R1, and R3 points (Left and Right Foot Landmarks) 92.8(–20.7): Angle of the CoP position (tangent value) L1 and R1: left and right middle point of posterior of heel, respectively; L3 and R3: left and right head of fifth metatarsal bone, respectively

Data analysis

The Shapiro-Wilk test was used to investigate the normal distribution of data, and the one-way analysis of variance (ANOVA) test was used to compare the mean anthropometric variables, kyphosis degree, isometric strength, and static balance parameters of the groups. In addition, the General Linear Univariate Model (GLUM) was performed to study the independent effects of the thoracic curve and BMD conditions on the static balance parameters. The GLUM analysis was adjusted for age to clarify the aging effect. The correlations of the variables were assessed by Pearson's coefficient correlation. Statistical significance was set at $P \leq 0.050$. IBM SPSS Statisticsver. 16(IBM, Armonk, NY, USA) was used for statistical analysis.

Results

Anthropometric variables are shown in Table 1. There were significant differences in age and menopause duration ($P \leq 0.05$) among the four postmenopausal groups. The nonosteoporotic normal kyphotic group was the youngest in the postmenopausal groups, and the lowest value of the menopausal duration was also observed in this group ($P \leq 0.05$). There were no significant differences in BMI and leg length, among the four postmenopausal groups ($P > 0.05$).

As seen in Table 1, thoracic kyphosis degree was significantly higher in Groups 1 and 4 compared to Groups 2 and 3 ($P \leq 0.05$); there was no statistical difference between Groups 1 and 4 ($P > 0.05$). The mean value of the kyphosis degree in the young group was significantly less than that in both of the hyperkyphotic groups ($P = 0.001$). There was no significant difference among the young and normal kyphotic women in the degree of thoracic kyphosis ($P > 0.05$).

Spine T-score was significantly lower in Groups 1 and 2 than in Groups 3 and 4 ($P \leq 0.05$), but there was no statistical difference between the two osteoporotic groups ($P > 0.05$).

According to Table 2, the isometric strength of hip abductors in both of the osteoporotic groups showed a significant decrease compared to both of the nonosteoporotic groups. The GLUM also showed that the BMD value was the primary significant factor in predicting the hip abductor strength values (F 6.33, P 0.017) (Table 3). Although the strength of the ankle plantar flexion was not significant among groups (Table 2), the GLUM showed a significant effect of BMD value on the ankle plantar flexor strength value (F 5.507, P 0.026) (Table 3). As seen in Table 2, isometric strength of the hip adductors and back extensors of the hyperkyphotic groups decreased significantly compared to both of the normal kyphotic groups. The GLUM showed a significant effect of thoracic kyphosis on the hip adductor (F 4.84, P 0.035) and back extensor strength value (F 6.70, P 0.014) (Table 3). There was

Table 1 Anthropometric variables in the postmenopausal groups, mean (SD)

Variables	Osteoporotic hyper kyphotic (*n* = 10) Group1	Osteoporotic normal kyphotic (*n* = 12) Group2	Nonosteoporotic normal kyphotic (*n* = 10) Group3	Nonosteoporotic hyper kyphotic (*n* = 7) Group4	*P* value	Young women
Age (years)	59.100 (6.38)	57.58 (5.97)	51.60 (3.47) €	58.85 (9.8)	0.049*	27.40 (2.5)
BMI (kg/m^2)	29.22 (3.68)	29.03 (6.03)	29.40 (3.80)	29.98 (2.74)	0.307	
Leg length (cm)	81.40 (4.97)	81.16 (5.63)	79.88 (4.42)	80.42 (2.07)	0.892	
Menopause duration (years)	12.50 (5.92)	10.91 (7.64)	3.9 (3.69) €	12.28 (6.94)	0.017*	
Kyphosis degree	58.75 (4.25) £	45.80 (4.14)	45.91 (4.84)	57.03 (4.44) £	0.001*	40.91 (8.36)
Spine T-Score	− 2.91 (0.650) ¥	− 2.61 (0.925) ¥	0.83 (1.12)	− 0.22 (0.64)	0.001*	

*Significant difference among four groups

€ Significant decrease compared to the other groups

£ Significant increase compared to the both of normal kyphotic groups

¥ Significant decrease compared to both of nonosteoporotic groups

no significant difference among the other muscle groups ($P > 0.05$) (Table 2).

According to Table 4, the AP mean CoP velocity and its SD in the postmenopausal hyperkyphotic groups was significantly higher than those observed in the young group ($P \leq 0.05$).

In the AP direction, Group 1 showed a significant increase in mean CoP velocity and its SD compared to Group 3 ($P \leq 0.05$) (Table 4). Based on the results of the GLUM, in contrast to the BMD value, the thoracic curve condition was the main factor for predicting the CoP sway velocity and its SD in the AP direction ($P \leq 0.05$) (Table 5).

In the ML direction, mean CoP velocity and SD in Groups 1, 2, and 4 were significantly higher than those observed in the young group ($P \leq 0.05$) (Table 4). In this direction, both of osteoporotic groups showed a significant increase in mean CoP velocity and its SD compared to Group 3 ($P \leq 0.05$) (Table 4). The results of the GLUM showed that the BMD condition was the main factor for predicting the CoP sway velocity values in the ML direction, rather than thoracic curve condition ($P \leq 0.05$) (Table 5).

There was no significant difference among the five groups in terms of Dp, Dp/Ap, and the CoP angle ($P > 0.050$) (Table 4). However, based on the results of GLUM, regardless of the BMD value, the thoracic curve condition was a significant main factor in predicting the Dp value ($P \leq 0.05$) (Table 5). The results of Dp/Ap were mostly similar to those of the Dp, and the GLUM showed that the thoracic curve was also a significant factor in predicting the Dp/Ap value ($P \leq 0.05$) (Table 5). In other words, both hyperkyphotic groups [1, 4] maintained their CoP closer to the center of the BoS, but the difference was not significant ($P > 0.05$) (Table 4).

In the hyperkyphotic groups [1, 4], the CoP is located in the second quarter of the trigonometric circle (90 to 180 degrees),

Table 2 Isometric strength of muscular groups, mean (SD)

Variables muscular groups (kilogram)	Osteoporotic hyper kyphotic (*n* = 10) Group1	Osteoporotic normal kyphotic (*n* = 12) Group2	Nonosteoporotic normal kyphotic (*n* = 10) Group3	Nonosteoporotic hyper kyphotic (*n* = 7) Group4	*P* value
Ankle dorsiflexors	10.23 (4.03)	9.63 (2.80)	9.74 (4.45)	9.08 (4.01)	0.943
Ankle plantar flexors	8.33 (2.23)	8.91 (2.15)	11.38 (3.28)	10.12 (2.34)	0.096
Hip abductors	9.25 (2.85) ¥	9.67 (2.44) ¥	12.87 (2.59)	10.28 (1.86)	0.023*
Hip adductors	9.00 (2.81) £	9.61 (2.67)	12.35 (3.64)	8.61 (2.80) £	0.05*
Hip extensors	10.36 (2.93)	9.34 (2.84)	11.68 (4.20)	10.78 (2.06)	0.415
Hip flexors	8.11 (2.64)	8.47 (1.54)	9.65 (3.67)	7.56 (2.07)	0.401
Knee extensors	16.43 (4.49)	15.71 (4.46)	17.46 (4.63)	14.62 (6.93)	0.716
Knee flexors	7.27 (2.33)	7.05 (2.15)	7.84 (2.95)	7.10 (1.54)	0.874
Back extensors	7.47 (1.49) £	8.11 (1.48)	9.86 (1.23)	7.66 (2.39) £	0.012*

*Significant difference among four groups

¥ Significant decrease compared to the both of nonosteoporotic groups

£ Significant decrease compared to the both of normal kyphotic groups

Table 3 Results of general univariate linear model (GLUM) (variables: muscular groups)

Muscular group	BMD condition		Thoracic curve condition		BMD*Thoracic Curve	
	F statistic	*P* value	F statistic	*P* value	F statistic	*P* value
Ankle plantar flexors	5.507	0.26*	1.023	0.320	0.141	0.710
Hip abductors	6.33	0.017*	3.20	0.082	1.65	0.207
Hip adductors	1.41	0.243	4.84	0.035*	2.48	0.124
Back extensors	3.12	0.087	6.70	0.014*	2.02	0.164

*Significant effect ($P \leq 0.05$), the GLUM analysis was adjusted for age

while in the other groups, especially in the young group, the CoP is located in the first quarter (0 to 90 degrees) (Table 4).

In postmenopausal participants, there was a significant negative correlation between the hip extensors' strength with Dp and Dp/Ap ($P \leq 0.05$) (Table 6). In the other muscle groups observed, there was no remarkable correlation with the CoP location parameters (Table 6).

Discussion

The main purpose of this study was to investigate the independent effects of thoracic kyphosis and osteoporosis on the static balance parameters in postmenopausal women. In this regard, in addition to the traditional CoP sway parameters, the CoP location into the BoS was chosen to study the postural balance of the hyperkyphotic and normal kyphotic women, with and without osteoporosis, and to compare these to the balance parameters of young healthy women. Because of the effect of leg strength on the postural balance parameters [29], we also studied the relationship between lower limb and back extensor muscle strength on the CoP location into the BoS in the four postmenopausal groups. According to the GLUM analysis, a decrease in the back extensors and hip adductors' strength was associated with thoracic hyperkyphosis, and the decrease in the hip abductors and ankle plantar flexors' strength was associated with the BMD value. Douchi et al. showed trunk lean mass declined with menopause more than in other sites, independent of aging and height [30]. Similarly, in our study, some muscle groups were affected earlier by menopause and its complications (such as osteoporosis and thoracic hyperkyphosis). According to Hirose et al., some gait alteration, observed in hyperkyphotic elderly in response to functional imbalance, included decreased step and stride length and increased step width [31]. So it is probable that some functional adoption in hyperkyphotic women, such as wide stance walking, induced overstretching and subsequently, weakening some lower limb muscles, such as hip adductors. Thus, it is reasonable to expect to observe a combination of back extensor and hip adductor weakness in hyperkyphotic women. In contrast, ankle plantar flexor and hip abductor muscles are associated with osteoporosis independent of the thoracic curve condition (confirmed, based on the GLUM). According to Liu et al., response of bone tissue is site-

Table 4 Static balance parameters, mean (SD)

Variables CoP parameters	Osteoporotic hyper kyphotic ($n = 10$) Group1	Osteoporotic normal kyphotic ($n = 12$) Group2	Nonosteoporotic normal kyphotic ($n = 10$) Group3	Nonosteoporotic hyper kyphotic ($n = 7$) Group4	Young women ($n = 10$)	*P* value
Mean velocity in A-P (cm/s)	0.0082 (0.0009)¥ £	0.0064 (0.0022)	0.0059 (0.0015)	0.0075 (0.0011)¥	0.0043 (0.0009)	0.001*
Mean velocity in M-L (cm/s)	0.461 (0.152)¥ £	0.468 (0.215)¥ £	0.340 (0.102)	0.418 (0.085)¥	0.309 (0.025)	0.001*
SD of mean velocity in A-P (cm/s)	0.0104 (0.0013)¥ £	0.0081 (0.0029)	0.0075 (0.0021)	0.0100 (0.0020)¥	0.0057 (0.0011)	0.001*
SD of mean velocity in M-L (cm/s)	0.564 (0.180)¥ £	0.510 (0.104)¥ £	0.423 (0.124)	0.515 (0.101)¥	0.383 (0.033)	0.001*
Dp(cm)	3.58 (1.95)	5.17 (1.32)	4.19 (2.03)	3.84 (1.03)	4.49 (1.66)	0.231
DP/Ap (1/cm)	0.0055 (0.0031)	0.0087 (0.0024)	0.0067 (0.0031)	0.0068 (0.0016)	0.0074 (0.0035)	0.157
Angle of CoP position into the center of Ap (degree)	98.61 (19.65)	93.84 (16.42)	90.68 (13.33)	96.71 (19.51)	86.31 (12.35)	0.618

*Significant difference among five groups

¥ Significant increase compared to the young group

£ Significant increase compared to the nonosteoporotic normal kyphotic group

Table 5 Results of general univariate linear model (GLUM)

Balance parameters	BMD condition		Thoracic curve condition		BMD*thoracic curve	
	F statistic	*P* value	F statistic	*P* value	F statistic	*P* value
CoP Vel in A-P	0.428	0.517	6.29	0.017*	0.292	0.592
SD of CoP Vel in A-P	0.084	0.774	6.89	0.013*	0.067	0.797
CoP Vel in M-L	3.96	0.05*	2.10	0.156	2.96	0.094
SD of CoP Vel in M-L	3.33	0.077	3.15	0.085	2.49	0.124
Dp	0.315	0.577	4.23	0.045*	1.16	0.286
Dp/Ap	0.068	0.795	3.79	0.05*	2.73	0.105
Angle of the CoP	0.070	0.792	1.61	0.212	0.112	0.740

*Significant effect ($P \leq 0.05$), the GLUM analysis was adjusted for age

specific to the muscular and mechanical loads, and they reported that the tibia and femur suffered the most bone loss due to ovariectomy in comparison to other skeletal sites [32]. Based on the site-specific response of bone tissue and the adaptive responses of bone-muscle structure as a functional unit [33, 34], it could be possible that the response of the muscles is site-specific to estrogen deficiency after menopause. On the other hand, it seems that muscles similar to the bones are more sensitive to loads or hormonal changes in some regions more than in other regions, and some muscle groups may be more involved than other muscles in postmenopausal osteoporosis.

In assessments of static balance, the mean velocity of the CoP displacement and its SD in the AP direction indicated higher values in both hyperkyphotic groups compared to the young group. Also, these values were significantly higher in Group 1 compared to Group3. Based on the results of the GLUM, the thoracic curve condition was the primary significant factor in the sagittal balance of the women; in contrast, it was observed that osteoporosis (BMD condition) was the primary factor in the frontal balance of the women. In the ML direction (frontal plane), the CoP sway velocity showed a significantly higher value in Groups 1, 2, and 4 compared to the young women. Among the postmenopausal women, both osteoporotic groups [1, 2] showed significantly higher values compared to Group 3. Therefore, it appears that osteoporosis, as well as aging, could induce postural instability in the frontal plane, although more accurate statistical analysis revealed that osteoporosis and thoracic hyperkyphosis affected the postural stability of the postmenopausal groups, independent of aging. To clarify the aging effect, the GLUM analysis was adjusted for age as a covariate. Furthermore, in the AP direction, only hyperkyphotic groups showed a significant difference compared to the young group, whereas other postmenopausal groups [2 and 3] showed no significant difference with the young group. In the current study, simple position and relatively short duration of the balance test (comfortable double stance, 20s), might lead to a failure to observe the effect of aging on the static balance parameters in the examined groups [35].

It should be considered that the mean age of the postmenopausal women of this study (56.66 ± 6.89 years) was lower than that of similar previous studies, so the degenerative process related to aging did not considerably affect the women of this study in observing the independent effect of aging on the investigated balance parameters.

Table 6 Correlations between isometric strength of muscles and CoP position parameters

Strength of muscles	Dp		Dp/Ap		COP position as degree	
	PCC	*P* value	PCC	*P* value	PCC	*P* value
Back extensors	0.010	0.953	− 0.090	0.601	0.008	0.963
Hip abductors	0.069	0.687	0.036	0.835	− 0.321	0.064
Hip adductors	− 0.016	0.923	− 0.044	0.794	0.020	0.911
Hip flexors	− 0.122	0.465	− 0.143	0.391	0.049	0.780
Hip extensors	− 0.352	0.033*	− 0.372	0.023*	0.012	0.946
Knee extensors	− 0.146	0.390	− 0.188	0.266	− 0.142	0.416
Knee flexors	0.010	0.954	− 0.052	0.758	− 0.063	0.721
Ankle dorsiflexors	0.175	0.293	0.031	0.852	0.068	0.698
Ankle plantar flexors	− 0.063	0.732	− 0.091	0.619	− 0.351	0.062

PCC, Pearson correlation coefficient

*Significant correlation

The CoP position parameters showed no significant differences among the five groups: but the GLUM showed a significant effect of the thoracic curve condition on Dp and Dp/Ap, so despite the insignificant results, it was observed that in the hyperkyphotic groups (Groups 1, 4), the CoP was positioned closer to the center of the BoS. Burke et al. assessed the position of the CoP in relation to the center of the ellipse in the limit of stability (LoS) test between osteoporotic and nonosteoporotic women, and the results showed that the CoP was displaced posteriorly in the right lateral direction in osteoporotic women [36]. Although, in our study, the CoP was located anteriorly into the center of the BoS in all the postmenopausal groups, it was located closer to the center of the BoS in the hyperkyphotic groups. Merlo et al. showed the mean position of the CoP in the AP direction into the midpoint of the heels, displaced posteriorly in subjects who experienced more than two falls in the previous year, and they concluded that some compensatory responses, such as knee flexion due to the thoracic hyperkyphosis or weakness of the plantar flexors, might lead to the displacement of the CoP to a shorter distance from the reference point to keep the CoP away from the LoS [37].

This interpretation could also verify our results about the displacement of the CoP position to a closer distance from the center of the BoS in the hyperkyphotic groups (Groups 1, 4). In contrast to the hyperkyphotic groups, in Groups 3 and 5, which had no postural deformities or muscular weakness, the CoP was located at a greater distance from the center of the BoS. Shaw et al. reported that, in some positions, younger adults utilize variability strategies for maintaining balance, in contrast to the elderly who tend to use stiffening strategies in most positions; in other words, more variability helps to the younger adults select different protective strategies, so an increase in postural sways does not always mean postural instability, especially in young healthy subjects [38]. In our study, it is probable that variability strategies led to an increase in Dp in Groups 3 and 5 compared to the hyperkyphotic groups [1, 4]. Wegen et al. showed that the younger subjects could lean closer to their stability boundary because their time to contact boundary (TtB: the minimum distance of the CoP from the stability limits in certain directions/the instantaneous velocity of the CoP) was longer than that of the older subjects which lead to safely keeping the CoP closer to the stability boundaries in younger subjects [39]. The greatest value of Dp was recorded in Group 2, but it was not significant.

Considering that the strength of hip extensors is negatively and significantly correlated with Dp, it seems that the strength of hip extensors could be an important factor in determining the CoP position into the BoS. Interestingly, maximum Dp was observed in Group 2, where the lowest amount of hip extensor strength was recorded, although it should be considered that the changed perception of the stability limits due to aging, which reduces sensitivity of the plantar mechanoreceptors [40], could also affect the CoP position of this group. The Dp/Ap results showed a similar trend with Dp. It was just a normalized data for Dp in order to eliminate the effect of the BoS size on the interpretation of the results. The CoP angle into the center of the BoS showed no significant difference among the five groups, and neither the kyphosis curve nor the BMD were recognized as significant factors to determine this parameter. In spite of insignificant difference among all five groups in terms of the CoP angle, it seems that the mean position of the CoP is displaced more than other groups to the second quarter of the trigonometric circle (90 to 180°) in the hyperkyphotic groups (groups 1 and 4), while, in the other groups, it is located around the position of 90°. In other words, in two hyperkyphotic groups, the CoP is shifted more than other groups to the left non-dominant side. It should be considered that all the subjects were right handed. The shift of the CoP to the non-dominant side acts as a signal for the motor control system to utilize a stepping strategy to maintain balance in the elderly, as a preselected strategy to reduce the time needed to complete the step strategy [41]. Also, based on the fact that the right side of the human body is often stronger than the left side, for right-handed people [42], it may be possible that hyperkyphotic subjects bent her trunk to the left side in order to maintain pelvic stability. This compensatory sign maybe the cause of left-facing CoP vector in the hyperkyphotic groups.

The small sample size, due to the specific inclusion criteria, was one of the study's limitations. In our study, postural assessment was limited to thoracic kyphosis measurement, but it seems that lumbar lordosis and pelvic tilt should be assessed in future studies. In addition to the CoP position parameters investigated in this study, the distance between the mean position of the CoP and the borders of the BoS should be considered in future studies, especially in dynamic condition, to obtain more functional information about altered balance strategies utilized by osteoporotic women who are at risk of falling. Measuring the CoP sway in free selected and fixed standing status (such as standing with two feet together) may be better to compare some compensatory strategies in postmenopausal women with and without hyperkyphosis.

Conclusion

Our results showed thoracic hyperkyphosis increased the CoP sway velocity in the AP direction, whereas osteoporosis increased the CoP sway velocity in the ML direction. The distance between the CoP and the center of the BoS is significantly and negatively correlated to the strength of the hip extensors. Further studies examining thoracic kyphosis, lumbar lordosis, and pelvic tilt and their effects on CoP sway and its location in the BoS are necessary, especially in respect to dynamic conditions.

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Compliance with ethical standards

The Medical Ethics Committee of Tarbiat Modares University approved the study.

Conflicts of interest None

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