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Postural Stability in Patients with Moderate Knee Osteoarthritis: Roles of Visual Feedback and Dynamic Perturbations

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ABSTRACT

Background: Knee osteoarthritis is the most common joint disease and a leading cause of disability in old age. The present study aims to analyze the stability of standing with and without perturbation in patients with moderate knee osteoarthritis.
Methods: Twenty-eight people (14 men with knee osteoarthritis and 14 healthy individuals) were evaluated for postural control in this observational cross-sectional study. In standing tests, the effects of disease (osteoarthritis vs. healthy), vision (open vs. closed eyes), and support condition (quiet standing vs. on the unstable plate) on balance were studied.
Results: The results showed that the presence of knee osteoarthritis significantly reduced the root mean square of hip joint flexion in patients compared to the control group (P= .024). The elimination of vision and reducing the base of support by standing on an unstable plate led to local instability in the joints close to the perturbation, especially the ankle ($P<0.001$). The center of pressure data also showed that the mean ($P=0.034$) and variability ($P=0.003$) of the anterior-posterior excursion was significantly higher in patients. Patients with knee osteoarthritis are more vulnerable to falling on an unstable plate.
Conclusion: The body uses a postural stiffening strategy to prevent falling forward, especially on an unstable plate, and postural adjusting in the medio-lateral direction. In rehabilitative treatments to prevent falls based on the sensory re-organization plans, e.g., rocking board, foam standing, game therapy, etc., it may be more efficient to focus on the distal joint muscles.
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Introduction

Osteoarthritis is the most common joint disease and a leading cause of disability in old age. This progressive disease leads to the loss of normal joint function by involving the joint and synovial membrane during a chronic degenerative process [1]. According to reports in Iran and the world, the most common joint involved in patients with osteoarthritis is the knee joint [2, 3]. The prevalence of osteoarthritis in Iran is estimated to be 16% in rural and 15% in urban areas [4]. Arthrogenic inhibition of the quadriceps muscle and its atrophy, in addition to reducing peripheral sensation, leads to poor posture control while standing and walking and increases the risks of falling in these patients [3, 5, 6]. The lack of proprioception leads to a change in gait pattern and places an additional load on the joint, followed by progressive joint damage [7]. Despite proprioceptive impairment in patients with knee osteoarthritis, postural control disorder is probable [8]. The high prevalence of falling in these patients also confirms the existence of postural control instabilities [9].

Hassan et al. stated that patients with knee osteoarthritis had higher weight and more postural sways, weaker

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proprioception and quadriceps compared to the control group, followed by a decrease in quadriceps muscle activation [10]. Heinman et al. also showed that the sways of the center of pressure (CoP) in the frontal plane in normal conditions and in the sagittal plane with the eye closed are higher in patients [11]. Kim et al. stated that patients with moderate to severe knee osteoarthritis had more instability than those with mild knee osteoarthritis [12]. Sanchez-Ramirez et al. reported that in patients with knee osteoarthritis, decreased torso control is associated with muscle weakness, proprioceptive dysfunction, and the degree of functional limitations [13]. Turcot et al. showed that patients with severe symptoms of knee osteoarthritis had a more flexed position compared to the control group with a significant decrease in the degree of anterior-posterior CoP displacement. In addition, they found that in osteoarthritis patients, postural adjustment was performed asymmetrically in several joints, and that this multi-joint coordination could protect the affected knee joint. However, this type of compensatory control on the non-involved side can have a devastating effect on other joints and lead to the onset of destructive diseases in them [14]. Pirayeh et al. stated that the standard deviation of CoP velocity in the anterior-posterior (AP) direction has the highest sensitivity in two standing positions on two legs with eyes open and closed. The standard deviation of anterior-posterior CoP velocity was the most appropriate indicator for differentiating patients with moderate to severe radiographic symptoms in standing positions with both eyes open and closed [15]. These studies, however, seldom applied physical perturbations to the standing. Moreover, the test duration was often too short (about 10 seconds) and may not have revealed the postural strategies during maintenace of balance.

Previous studies have generally used linear variables to analyze standing stability, like the pathlength (PL), root mean square (RMS), variability (Var), and phase plane portrait (PPP) [16-18]. Standing on an unstable surface requires the use of more torque forces compared to quiet standing because of the impaired proprioception in these patients [19, 20]. According to studies on the balance of patients with osteoarthritis, however, the rate of postural sways in the closed eye was higher compared to the open eye [11, 15]. Visual feedback is one of the main sensory sources complementing closed loop control. This sensation, along with the proprioception as well as the vestibular system, helps to establish stability in standing [21]. Previous studies have shown that the use of proprioception in healthy people is 70%, and the remaining 30% is divided between the visual and vestibular senses [22]. As proprioception is significantly impaired in patients with knee osteoarthritis [23], it is hypothesized that the role of visual feedback will be compensatory. Moreover, standing in a static position without physical disturbance may not lead to a maximal or adequate use of neuromuscular effort. To date, studies have not investigated the effect of standing in more difficult physical conditions on stability or how to maintain it in patients with moderate knee osteoarthritis. Therefore, the present study aimed to assess the stability of standing with and without visual sensory and the physical perturbations of the support in patients with moderate knee osteoarthritis. It was hypothesized that i) the patients with knee osteoarthritis are more unstable than healthy individuals, ii) elimination of visual feedback reduces stability, and ii) physical perturbation to the support from an unstable plate also reduces the stability.

Methods

Participants

Twenty-eight individuals, including 14 patients with knee osteoarthritis and 14 asymptomatic healthy men, were selected to participate in this observational cross-sectional study using the convenience sampling method. A post-hoc power analysis (with 95% confidence interval) confirmed the sufficiency of the number of participants. The patients were included if they had moderate knee osteoarthritis based on the K-L criteria in radiographic images (level II or III) [24]. The Ethics Committee of Tarbiat Modares University approved this study (code: IR.MODARES.REC.1398.094) and, after participants were provided with a full explanation of the study and its objectives, they signed informed consent forms. Inclusion criteria for patients consisted of unilateral knee osteoarthritis, visual analog scale of more than 3 in over half of the last month, the ability to stand and walk short distances without aid (walker or wheelchair), K-L criterion equal to three, age between 50 to 70 years, normal blood pressure, no postural hypotension, less than VAS 2 on test day, no prosthesis or history of joint replacement, no athletic activity (not participating in regular exercise or musculoskeletal and yoga strengthening programs in the last 6 months), no neuromuscular-muscular disorder (other than the knee osteoarthritis). Inclusion criteria for the control group were only age between 50-70, normal blood pressure, and no neuromusculoskeletal disease.

Procedure

Participants were asked to stand barefoot with arms crossed on the chest. Four test conditions were 1) open eyes – quiet standing (EO-QS); 2) closed eyes - quiet standing (EC-QS); 3) open eyes on an unstable spring-supported surface (EO-UP); and 4) closed eyes on an unstable spring-supported surface (EC-UP). The control group also performed the four above-mentioned conditions. The standing conditions were randomly selected for each individual. The unstable support was a flat surface measuring 55 x 40 cm with a height of 10 cm, placed on two semi-ellipses with a small diameter of 26 cm. This surface was always supported by a pair of springs from below that were placed in front and behind the surface. Figure 1 shows the unstable surface and its supporting springs. The standing time in each test position was 30 seconds [11, 13, 25], and each position was repeated in three trials. There was a one-minute rest (sitting in a chair) between the trials. The test was repeated if the arms were opened or the sole of the foot detached from the ground/unstable surface.

Data Acquisition

An eight-camera motion analysis system (Vero

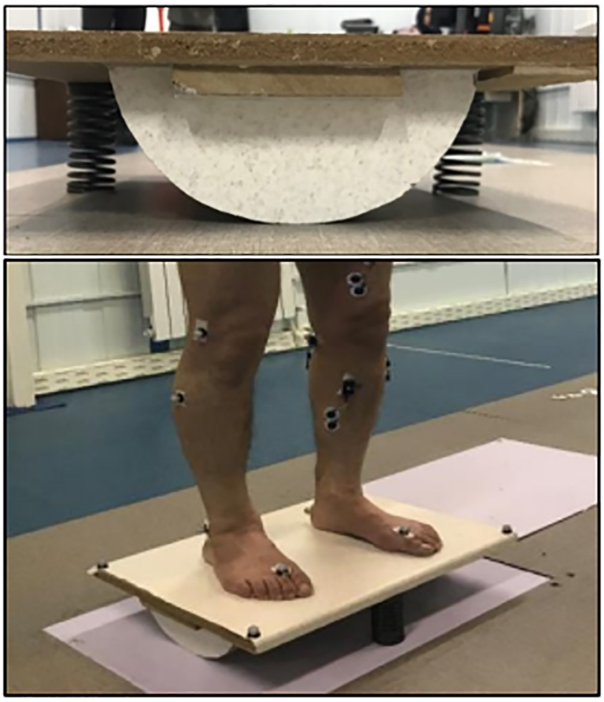

Figure 1: Unstable plate and its supporting springs (top); the volunteer standing on an unstable plate all on the force-plate (bottom)

model, Vicon, UK) was used to record the movement of the joints at a data rate of 120 Hz. The markers were mounted on the bone landmarks according to the instructions of the lower limb plug-in-gate model. Appendix A presents the location of marker attachments in detail. Although the imaging was three-dimensional, only the flexion/extension angles of the three lower limb joints (movements performed on the sagittal plane) were analyzed to seek relevancy and simplicity. In addition, the CoP data was recorded in all cases by a force-plate (Kistler, Switzerland) at a data rate of 1200 Hz.

Data Analysis

Either the CoP or the kinematic data was used without any filtration. The variables of pathlength (PL), root mean square (RMS), variability (Var), and phase plane portrait (PPP) were calculated to evaluate the local and global stability of the body based on joint movement data (ankle, knee, and thigh of the involved/dominant leg) and excursions of the CoP using the relationships presented in Table 1, in which x is the general variable, i.e. either the CoP displacements in the anterior-posterior or mediolateral (ML) direction or joint angles.

In addition, a load-bearing index (LBI) was defined as a measure of reliance on the involved leg among patients with knee osteoarthritis. The LBI was calculated by dividing the CoP displacement in the mediolateral direction toward the involved leg by half of the width of the support base. Accordingly, the LBI shows the percent of the weight borne by the involved leg out of normal, and vice versa. Figure 2 illustrates the concept of the LBI.

Statistical Analysis

The Kolmogorov–Smirnov (K-S) test was used to check the normality of data distributions. Linear mixed model analysis of variance was utilized to assess the role of osteoarthritis, vision and support condition on the joint kinematics, CoP variables, and the LBI. The level of significance was set to 5%.

Results

The distribution of the data, including the demographical and postural metrics, was normal based on the K-S test ($P>0.162$).

Demographical Data

The means (standard deviation) of demographic data of healthy and patients are given in Table 2. Two groups were

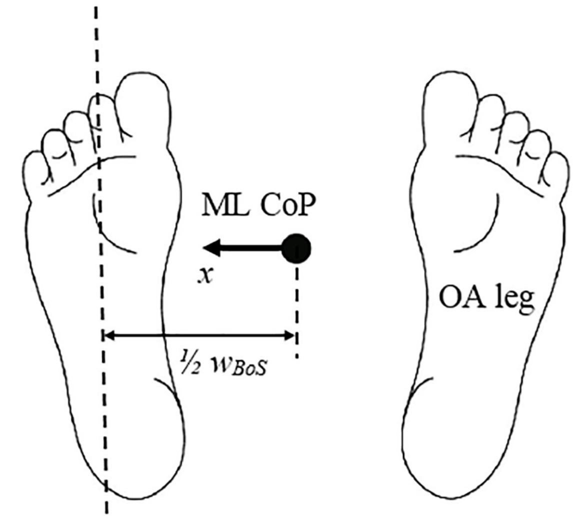

Figure 2: The concept of load-bearing index (LBI): x is the mediolateral center of pressure (CoP) distance and w_{BoS} is the width of the base of support.

Table 1: Definition of the analysis variables based on the general variable x which may be both the center of pressure (CoP) excursion and the joint angles; n is the number of data per 30-second test duration. The dot sign above x means time derivative, i.e. the velocity. Information adopted from refs [16, 17].

Variable	Formula	Interpretations
Pathlength (PL)	$\mathrm{PL} = \sum_t \lvert x_{t+1} - x_t \rvert$	Stability: energy consumption
Root mean square (RMS)	$\mathrm{RMS} = \sqrt{\frac{\sum x_t^2}{n}}$	Stability: displacement's magnitude independent from the direction
Variability (Var)	$\sigma_x = \sqrt{\frac{\sum (x_t - \bar{x})^2}{n}}$	Stability: sameness or variability of the displacement
Phase Plane Portrait (PPP)	$\mathrm{PPP} = \sqrt{\sigma_x{}^2 + \sigma_{\dot{x}}{}^2}$	Stability: simultaneous control over displacement and velocity

Table 2: The mean (standard deviation) of the demographic data.

	Age (years)	Height (cm)	Mass (kg)	BMI (kg/m²)
Patients with knee osteoarthritis	55.8 (5.1)	170.8 (7.1)	79.0 (8.5)	27.1 (2.5)
Healthy controls	54.8 (5.5)	171.4 (5.1)	79.5 (9.6)	27.0 (2.4)
P value	0.68	0.83	0.82	0.95

age-matched (P=0.68) at near 55 years. Moreover, there was no difference in the anthropometric characteristics of the participants between the healthy and patient groups (P>0.82).

Local Approach

The local approach is based on motion analysis data in three joints affecting standing in the lower limbs (ankle, knee, and thigh). Figure 3 shows the changes in stability variables while standing in different conditions.

The main and interaction effects of independent variables on PL, RMS, Var, and PPP of joint motion data are collected in Table 3. The bold numbers indicate the significant effects. The osteoarthritis significantly reduced the RMS of hip flexion in patients, who had an average of 1.17 degrees, compared to the control group, which averaged 1.34 degrees (P=0.024). Knee osteoarthritis had no effect on the RMS of the knee and ankle joints (P<0.050). Variability of the hip was also almost significant (P=0.070); again, these values were lower in the patients than in the healthy age-matched individuals.

Global Approach

The global approach is based on the CoP data in both AP and ML directions. Figure 4 shows the changes in stability variables while standing in different conditions. The changes in the PL and PPP are greater for the AP direction than for the ML, while in the RMS and Var, they are reversed.

The main and interaction effects of independent variables on the CoP stability metrics are shown in Table 4. The bold numbers indicate the significant effects of independent variables. The RMS in the AP direction increased significantly in patients with osteoarthritis compared to the control group (P=0.034), but it had no significant change in the ML direction.

According to Figure 5, by going on an unstable plate and removing the visual feedback, the LBI was significantly different compared to the same position with the eyes

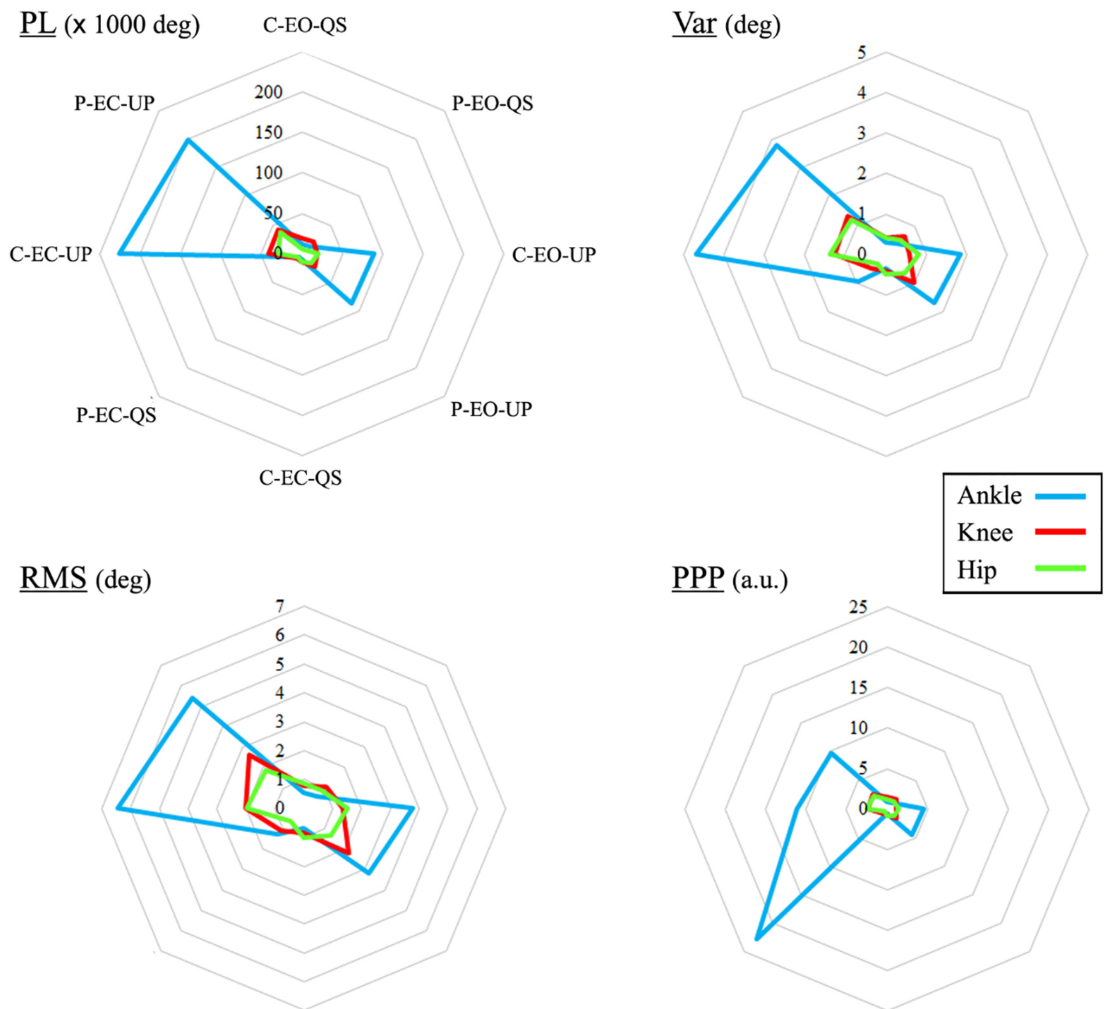

Figure 3: Polar plot of changes in four stability linear variables of path length (PL), root mean square (RMS), variability (Var), and phase plane portrait (PPP) for ankle, knee, and hip joints in four test conditions and two groups, control (C) and patient (P). For a better and simpler demonstration, the titles of the conditions appear only for the top-left plot. EO: Eyes-open; EC: Eyes-closed, QS: Quiet Standing; UP: Unstable plate

Table 3: Main and interaction effects' P values of local stability metrics based on motion data of ankle, knee, and hip joints in involved leg.

	PL			RMS			Var			PPP		
	Ankle	Knee	Hip	Ankle	Knee	Hip	Ankle	Knee	Hip	Ankle	Knee	Hip
Osteoarthritis	0.581	0.348	0.852	0.487	0.276	0.024	0.748	0.304	.070	0.360	0.449	0.439
Vision	0.001	0.017	0.260	0.001	0.154	0.167	0.001	0.015	0.068	0.158	0.202	0.807
Support	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.854	0.001	0.006
OA×Vision	0.577	0.405	0.679	0.948	0.630	0.791	0.859	0.456	0.305	0.383	0.397	0.584
OA×Support	0.590	0.767	0.695	0.113	0.860	0.278	0.099	0.559	0.690	0.319	0.824	0.691
Vision×Support	0.001	0.001	0.001	0.004	0.080	0.194	0.001	0.003	0.007	0.692	0.001	0.001
OA×Vision×Support	0.688	0.903	0.937	0.492	0.336	0.833	0.212	0.487	0.655	0.309	0.770	0.906

PL: Pathlength; RMS: Root mean square; Var: Variability; PPP: Phase plane portrait; OA: Osteoarthritis

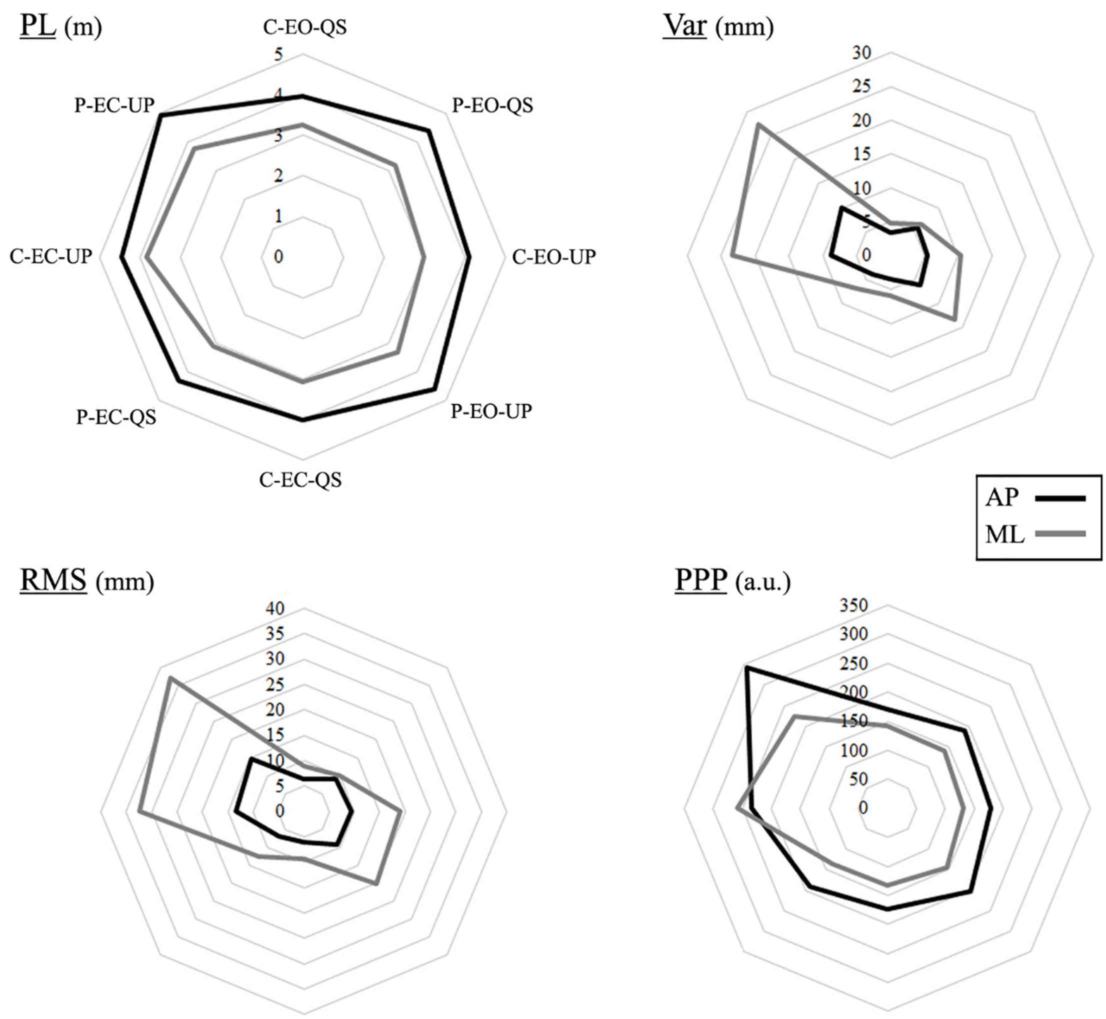

Figure 4: Polar plot of changes in four stability linear variables of path length (PL), root mean square (RMS), variability (Var), and phase plane portrait (PPP) for AP and ML directions of the CoP in four test conditions and two groups [control (C) and patient (P)]. For a better and simpler demonstration, the titles of the conditions appear only for the top-left plot. EO: Eyes-open; EC: Eyes-closed; QS: Quiet standing; UP: Unstable plate

Table 4: Main and interaction effects' P-values of global stability metrics based on the center of pressure (CoP) data.

	PL		RMS		Var		PPP	
	AP	ML	AP	ML	AP	ML	AP	ML
Osteoarthritis	0.809	0.144	0.034	0.193	0.003	0.059	0.860	0.233
Vision	0.324	0.541	0.001	0.063	0.001	0.025	0.072	0.164
Support	0.203	0.239	0.001	0.001	0.001	0.001	0.049	0.105
OA×Vision	0.794	0.932	0.256	0.972	0.886	0.532	0.677	0.552
OA×Support	0.799	0.875	0.680	0.563	0.146	0.800	0.860	0.475
Vision×Support	0.100	0.591	0.001	0.002	0.001	0.001	0.040	0.171
OA×Vision×Support	0.654	0.997	0.769	0.390	0.596	0.284	0.623	0.529

PL: Path length; RMS: Root mean square; Var: Variability; PPP: Phase plane portrait; AP: Anterior-posterior; ML: Mediolateral; OA: Osteoarthritis

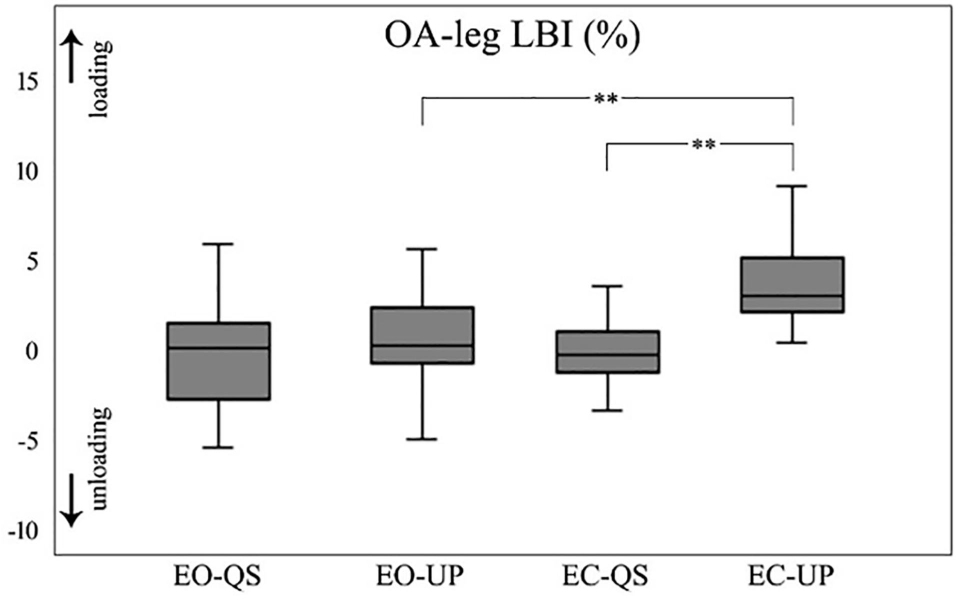

Figure 5: Percent of load-bearing index (LBI) in four test conditions. The sign ** indicates significance (P<0.001).

open and also compared to the quiet standing with the eyes closed (P<0.01). The patients unload less than 5% of their weight for the involved leg in the simplest standing position.

Discussion

The present study examined the postural stability of patients with moderate knee osteoarthritis and healthy age-matched controls. The ability to maintain balance in the anterior-posterior direction was adversely affected by knee osteoarthritis. The hip mechanism was also stiffened in these pateints to prevent falling. Imposing pseudo-random dynamical perturbations to the support and the absence of visual feedback also reduced stability.

Stability with the Local Approach

Considering the four stability variables in standing on the unstable plate, it can be said that the ankle joint succumbed to the perturbation and became unstable. Such instability was exacerbated by the lack of visual feedback. PL, RMS, Var, and PPP in standing positions were significantly longer for the ankle than for the other two joints because of the immediate proximity of this joint to the unstable plate. The amount of change in the other two joints was almost the same, and they are more stable when standing quietly. According to the local outcomes, the farther away the joint is from the site of perturbation, the more stable it becomes to contribute to the stability of the whole body.

It seems that the central nervous system (CNS) approach to controlling posture was to limit the use of the hip mechanism in patients with knee osteoarthritis. The osteoarthritis had no effect on the other joint mechanisms. Maintenance of the posture necessitates keeping the body's center of mass within the base of support. The position of the center of mass relies on the position and weight of the constituent body segments (here: shank, thigh, and trunk). As the motion of the lower segments were considerably influenced by the physical perturbations of the support, the CNS strived to confine the movement of the trunk which, incidentally, comprises a huge share of body weight. Therefore, controlling the heavy segment of the trunk can effectively confine the movement of the center of mass in order to provide stability.

Vision also had no effect on the PPP of any of the joints. This variable for the knee and hip was only sensitive to changes in the support condition that had a significant effect on the PL, RMS, Var, and PPP for all three joints. This meant that the rotation of the joints received the greatest impact from the change in the support condition. As the proprioception plays the greatest role in postural sensory feedback [22], standing on the unstable plate caused more instability because of higher interference with the proprioceptive feedback. The proprioception refers to the perception of neural feedback by receptors on the skin, joints, and muscles that leads to a general understanding of the position of the limbs and of the body [26]. In the meantime, to prevent falling through the CNS, it is necessary to increase the share of visual feedback. The significant *p*-values of interaction between the visual and support conditions highlight this idea, as previously stated in the study of Hirata et al. [27].

Stability with the Global Approach

The longer PL along with lesser RMS and Var for the AP direction meant that the participant had used a stiffening strategy (by keeping the joints fixed) instead of adjusting the posture (with more joint rotations). These are generally two basic strategies for controlling posture. The former increases joint stiffness through co-contraction of the muscles to reduce their rotations and the overall body sway. The postural adjustment strategy, on the other hand, allows the joints to have a degree of rotations to provide stability by consuming less energy [28]. Mohsenipour et al. stated that the probable cause of shorter the CoP pathlength and RMS could be the co-contraction of quadriceps and hamstrings to increase the stability of the involved joint while applying the stiffening strategy [29]. Conversely, in the ML direction with less PL but higher RMS and Var, it can be concluded that the CNS has not used the joint stiffening approach. The longer PL reflects higher energy consumption [16]. The joint stiffening strategy aims to limit the overall body sway by increasing the co-contraction of the agonist and antagonist muscles (for example, in the knee between the quadriceps and the hamstrings), which requires more energy. The PPP variable, which is a more direct measure of stability, indicated some instabilities in the AP direction, though it may make sense by noting on the same direction (pitch) of the unstable plate wobblings.

In quiet standing with open eyes, healthy age-matched individuals had no problems in stability provision under the use of visual feedback, leading to confined excursions of the CoP in both AP and ML directions. Removing the visual feedback and reducing the base of support by standing on the unstable plate led to greater muscular effort and changes in lower limb angles in the healthy participants in trying to maintain stability. In the most difficult position (i.e. EC-UP), the CoP excursion was relatively greater in the AP direction than in the ML direction. On the other hand, the amount of ML displacement was higher in patients with knee osteoarthritis when standing quietly with eyes open than in the healthy group, because the patients relied on the non-involved foot to stand and used it more. This finding is similar to the results of Taglietti et al. [8]. The main effect of the independent variable of osteoarthritis on the RMS and Var in the AP direction was significant ($P<0.034$), in contrast to the ML direction. Vision had a significant effect on the RMS in the AP direction and on Var in both directions as well as on sway area and LBI ($P<0.001$). The main effect of support condition on RMS and Var in both AP and ML directions and the PPP and LBI in the AP direction was significant ($P<0.001$). These results showed that the most effective factor in maintaining balance is support condition, followed by vision. Knee osteoarthritis could be distinguished in a few of the dependent variables obtained from the CoP excursion only in the AP direction. Vision and support condition played a key role in changes in variability. This finding is consistent with the results of a study by Heinman et al. which aimed to investigate balance disorders in patients with knee osteoarthritis while standing on hard and soft surfaces. They observed that dynamic standing as well as closing the eyes caused more instability in these patients than in healthy individuals [11]. In another study, Hsu et al. measured the movement of the center of mass after eliminating visual feedback and showed higher instabilities with the closure of the eyes in terms of more variability [30].

Turcot et al. showed that while standing quietly, a group of patients with knee osteoarthritis transmitted about 10% of their body weight on the non-involved knee [14]. Blaszczyk et al. calculated the same criterion for a group of young and a group of old people and stated that by calculating the load-bearing index only in the case of closed eyes, they determined that the elderly asymmetrically divide the weight between the legs [31]. It should be noted that both previous studies calculated this index from two force-plates below each leg (and based on the amount of ground reaction force). Standing in the most difficult position (on an unstable plate with the eyes closed), however, resulted in more load on the affected leg. In other words, when the test becomes difficult, patients give priority to balance rather than loading the involved leg. It could be concluded that adding a level of difficulty (eliminating visual feedback or reducing the level of reliance) does not lead to a change in the decision of the CNS to unload the affected leg. Therefore, the difficulty of the test in the fourth case (EC-UP) prevents the continuation of the usual loading strategy from the involved leg.

The present study had some limitations. The participants were only male whose kinematic measures of the lower extremity and pelvic girdle differ with the females, and hence, the results and interpretations of this study may not be necessarily the same for the female population. The motion analysis may also be associated with errors due marker placements and estimating the instantaneous center of rotation of the knee and hip joints.

Conclusion

Local analysis of postural stability in patients with moderate knee osteoarthritis based on motion analysis showed that the CNS restricts hip flexion in these patients. In such case, the study participants used the postural stiffening strategy instead of adjusting it, which would be accompanied by co-contractions and more energy expenditure. If standing for a long time, this expenditure of energy may cause fatigue and falls. Eliminating visual feedback led to local instability in the joints closer to the perturbation. In the global analysis, stability in patients with knee osteoarthritis was not sensitive to vision or support conditions. In other words, if the overall analysis of the body's stability in standing is considered, patients are more vulnerable to falling in the state of a reduced base of support. The analogy between the probability of falling from the front or back requires further analysis. What this study showed were faster but more limited and more controlled ML changes. Neuromuscular strength and adaptation in the abductor muscles of the hip and trunk seem to be decisive in this regard. Loading on a non-involved leg is possible in patients in simple cases, but it worsens as it becomes difficult to stand and load on the affected leg.

From a practical point of view, the importance of changing the contribution of the proprioception relative to the vision in the design of rehabilitation exercises is highlighted. Many of the balance exercises given to these patients can be accompanied by better sensory retraining. Increasing the acuity of the proprioception and its muscular coordination can prevent it from falling into unstable conditions such as the tests in this study. For example, the use of an unstable plate, Swiss ball, foam, game therapy, etc., in situations that do not lead to further pain will help sensory retraining along with muscle strengthening in these patients.

Conflict of Interest: None declared.

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Appendix A

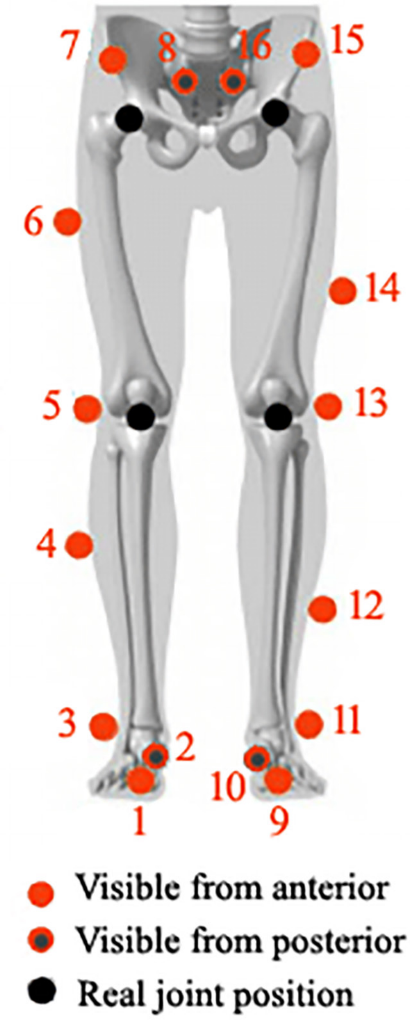

Figure A1: Frontal view demonstration of the markers

Vicon lower body plug-in-gait model.

Table A1: Anatomical locations of the markers and related segments

Marker Number	Marker Name	Location	Related segment(s)
1	RTOE	Distal of the 1st right metatarsal bone	Foot
2	RHEE	Right calcaneus	Foot
3	RANK	Right lateral maleolus	Foot/Shank
4	RTIB	Two thirds of the distance between the right lateral maleolus and the right lateral femoral condyle	Shank
5	RKNE	Right lateral femoral condyle	Shank/Thigh
6	RTHI	Two thirds of the distance between the right lateral femoral condyle and the right ASIS	Thigh
7	RASI	Right ASIS	Pelvis
8	RPSI	Right PSIS	Pelvis
9	LTOE	Distal of the first left metatarsal bone	Foot
10	LHEE	Left calcaneus	Foot
11	LANK	Left lateral maleolus	Foot/Shank
12	LTIB	One third of the distance between the left lateral maleolus and the left lateral femoral condyle	Shank
13	LKNE	Left lateral femoral condyle	Shank/Thigh
14	LTHI	One third of the distance between the left lateral femoral condyle and the left ASIS	Thigh
15	LASI	Left ASIS	Pelvis
16	LPSI	Left PSIS	Pelvis