Eklem Hastalıkları ve Cerrahisi
Joint Diseases and Related Surgery

Original Article / *Özgün Makale*

Eklem Hastalık Cerrahisi
2013;24(3):144-148
doi: 10.5606/ehc.2013.32

Prediction of postural sway velocity by foot posture index, foot size and plantar pressure values in unilateral stance

Tek ayak üzerinde duruşta postural salınım hızının ayak postur indeksi, ayak büyüklüğü ve plantar basınç değerleri ile tahmini

Salih Angın, PT, PhD., Nursen İlçin, PT, PhD., Sevgi Sevi Yeşilyaprak, PT, PhD., İ. Engin Şimşek, PT, PhD.

Dokuz Eylül Üniversity, School of Physical Therapy and Rehabilitation, İzmir, Turkey

Objectives: This study aims to assess whether the plantar pressure, the foot posture index (FPI) and foot size can predict the postural sway velocity in terms of postural stability in unilateral stance.

Patients and methods: A total of 236 feet of 118 participants (62 males, 56 females; mean age 22.1±3.1 years; range 18 to 36 years) were enrolled. The feet were classified as prone, normal and supine based on the FPI. Postural sway velocity during unilateral stance with eye open (US-EO) and eye closed (US-EC) condition was measured using the Balance Master. Plantar pressure for each foot was measured from 10 different areas using EMED-M pedobarography. The force-time-area (FTA) integral was calculated based on the plantar pressure values, while standardized foot size (SFS) was calculated dividing foot width by foot length. The one-way ANOVA was used to determine differences in postural sway velocity between the groups. Multiple linear regression analysis was used to evaluate the predictability of the postural sway velocity.

Results: The postural sway velocities in US-EO condition were similar among three groups ($p>0.05$). In the US-EC condition, the highest postural sway velocity in the prone feet and lowest postural sway velocity in the supine feet were measured ($p<0.05$). There was a significant relationship between the postural sway velocity which was measured in the US-EC condition and SFS ($\beta= 0.141$, $p<0.05$), FTA integral under the hindfoot ($\beta= -0.127$, $p<0.05$) and FPI values ($\beta= 0.246$, $p<0.05$).

Conclusion: The predictive value of FTA integral and SFS parameters for postural sway velocity is lower in unilateral stance. The postural sway velocity is rather associated with FPI and increases by pronation of the foot.

Key words: Flat foot; foot; postural balance; posture.

Amaç: Bu çalışmada tek ayak üzerine duruşta postural stabilite açısından postural salınım hızının plantar basınç, ayak postur indeksi (API) ve ayak büyüklüğü ile tahmin edilip edilemeyeceği araştırıldı.

Hastalar ve yöntemler: Çalışmaya 118 kişinin (62 erkek, 56 kadın; ort. yaş 22.1±3.1 yıl; dağılım 18-36 yıl) toplam 236 ayağı dahil edildi. Ayaklar API indeksine göre düztaban, normal ve yüksek taban olarak sınıflandırıldı. Postural salınım hızı, tek ayak üzerine duruşta gözler açık (TA-GA) ve gözler kapalı (TA-GK) durumda Balance Master ile ölçüldü. Her ayak için 10 farklı plantar bölgenin basınçları ise, EMED-M pedobarograf kullanılarak ölçüldü. Plantar basınç değerlerinden kuvvet-zaman-alan (KZA) integrali belirlendi ve ayak genişliği ayak uzunluğuna bölünerek standart ayak büyüklüğü (SAB) hesaplandı. Gruplar arasında postural salınım hızı farklılıklarını belirlemek için tek yönlü ANOVA kullanıldı. Postural salınım hızının tahmin edilebilirliğini belirlemek için çoklu doğrusal regresyon analizi kullanıldı.

Bulgular: Postural salınım hızı TA-GA durumda her üç grup için benzer bulundu ($p>0.05$). TA-GK durumda en yüksek postural salınım hızı düztaban ayak grubunda, en düşük salınım hızı ise yüksek taban ayak grubunda saptandı ($p<0.05$). TA-GK durumda ölçülen postural salınım hızı ile SAB ($\beta= 0.141$, $p<0.05$), topukta belirlenen KZA integral değeri ($\beta= -0.127$, $p<0.05$) ve API ($\beta= 0.246$, $p<0.05$) arasında anlamlı ilişki saptandı.

Sonuç: Tek ayak üzerine duruşta KZA integral ve SAB parametrelerinin postural salınım hızını öngördürücü değeri düşüktür. Postural salınım hızı daha çok API ile ilintili olup, ayaktaki pronasyon ile artar.

Anahtar sözcükler: Düztaban; ayak; postural denge; postur.

- *Received: May 30, 2013 Accepted: July 19, 2013*
- Correspondence: Salih Angın, PT, PhD. Dokuz Eylül Üniversitesi Fizik Tedavi ve Rehabilitasyon Yüksekokulu, 35340 İnciraltı, İzmir, Turkey.
Tel: +90 537 - 706 86 67 Fax: +90 232 - 412 49 46 e-mail: salih.angin@deu.edu.tr

The foot, the most distal segment of the lower extremity, provides a relatively small base of support for balance reactions. For this reason, many postural control strategies are dependent on and sensitive to mechanical alterations in the support surface which may affect surface contact area or change muscular strategies in order to maintain a stable base of support.[1,2] Central and peripheral nervous systems communicate and continuously integrate to align the body segments over the support surface.[2] Although there are more than one peripheral component in maintaining balance, one of them is usually set by the central nervous system as the priority sense of orientation to be used in the control process of body position and posture over the support surface.[3] This postural control process causes the plantar foot surface to appropriately transfer body weight to the ground which may be measured as plantar pressure. The magnitude of plantar pressure measurements varies depending on the region of the plantar surface from which the measurement is taken and is mainly influenced by foot posture and instant position of the center of gravity (COG) over the support surface.

Previous studies have shown the relation between foot posture and plantar pressure measurements.[4,5] Foot posture has also been indicated as a contributing factor in postural stability. In the supine foot, large COG sway patterns were detected as explained by the absence of the medial block.[1,6] On the other hand, a pronated foot with hypermobile characteristics was associated with less stability compared to a supinated foot with a more rigid structure.[2,7]

While the conflict about foot posture as an influencing factor on postural stability and plantar pressure characteristics goes on, to our knowledge no study has previously studied the possible relation between postural stability and plantar pressure characteristics. Therefore, the purpose of the present study was to assess the capability of plantar pressure patterns in 10 masks of the foot sole, foot posture index (FPI) and foot size to predict the postural sway velocity in unilateral stance.

PATIENTS AND METHODS

Participants

A total of 236 feet from 118 subjects (62 males, 56 females; mean age 22.1±3.1 years; range 18 to 36 years) were included in the study. They had no repeated lower extremity injuries and were free of all lower extremity injury in the past 12 months. They had no history of lower extremity surgery. They had no visual or vestibular disorders. The study was approved by the university's institutional ethical committee (815-GOA, 2012/40-11) and conducted in accordance with the principles set forth in the Helsinki Declaration 2008. Each participant signed an informed consent before participating in the study. Their feet were assessed using a six-item foot posture index (FPI) as described elsewhere.[8]

Procedure

Unilateral stance (US) test: The Balance Master System (version 8.6, NeuroCom Inc, Clackamas, USA) which has been used extensively for balance and weight bearing assessment[9,10] was employed to measure CoG sway velocity (degree per second) during US with eyes open (EO) and eyes closed (EC). Low sway velocity was considered as better postural stability. The participants were asked to stand on their left foot over the force platform with EO and then with EC as described.[9] If the subjects lost their balance within 10 seconds, the trial was marked as a fall. The same assessments were also performed for the right foot.

Plantar pressure distribution: Barefoot plantar pressure distributions were measured by an EMED-M pressure plate with 3792 sensor cells at 50-60 Hz in the 38x24 cm sensor area (Novel GmbH, Munich, Germany). The two-step protocol was used for plantar pressure measurement as described.[11] The data from an average of the four steps on the foot were used to represent the pressure pattern. The dynamic plantar pressure footprints obtained from each participant were divided into 10 masks (Novel, diabetes report software, Novel GmbH, Germany) as follows: Heel (HF), midfoot (MF), first metatarsal head (MH_1), second metatarsal head (MH_2), third metatarsal head (MH_3), fourth metatarsal head (MH_4), fifth metatarsal head (MH_5), Big toe (BT), second toe (ST) and toes 3-5 (T_{345}). Force-integral in Newton seconds (FTI, Ns) exerted from plantar pressure data was divided by corresponding contact area in square centimeters (CA, cm^2) to calculate Force-Time-Area Integral (FTAI, Ns/cm^2) to obtain more accurate mean cumulative load time per square centimeter as described elsewhere.[12]

Standardized foot size (SFS): Foot width was measured from widest region at the metatarsal region and length measured from heel to toe on the footprint using EMED database essential software (Novel GmbH, Germany). Standardized foot size was calculated as foot width (cm) divided by foot length (cm).

Data analysis

Both feet of the 118 participants were pooled into 236 samples for data analysis. Based on the

TABLE I

Post-Hoc (Tukey HSD) multiple comparisons of sway velocity, foot posture index and standardized foot size for three-foot postures

	Prone (n=52)	Normal (n=146)	Supine (n=38)			
	Mean±SD	Mean±SD	Mean±SD	p^1	p^2	p^3
Unilateral stance (degree/second)						
Eyes open	1.16±1.25	0.96±0.58	0.94±0.80	0.294	0.990	0.427
Eyes closed	6.42±3.81	5.66±3.50	3.96±2.52	0.357	0.019*	0.003*
Foot posture index	9.65±1.08	3.12±2.36	-2.84±1.60	0.000**	0.000**	0.000**
Standardized foot size	0.38±0.18	0.37±0.19	0.39±0.22	0.966	0.580	0.787

SD: Standart deviation; p1: Prone feet vs. normal feet; p2: Normal feet vs. supine feet; p3: Supine feet versus prone feet; * Significant at 0.05 level (two tail); ** Significant at 0.001 level (two tail).

FPI score, feet were classified as normal feet, supine feet and prone feet. Possible differences in postural sway velocity between the groups of feet were studied by means of an ANOVA (Tukey HSD post hoc test). The FTAI values for 10 masked areas and the FPI were input as independent variables alongside the SFS into a multiple linear regression analysis to predict postural sway velocity in the unilateral stance in eye open (US-EO) and closed (US-EC) conditions (dependent variables). The regression analysis was run following the backward stepwise elimination procedure. The significance level was set at 5% ($p<0.05$). All statistical analysis was performed using IBM SPSS software version 20.0 (IBM Corporation, Armonk, NY, USA).

RESULTS

The mean body mass index (BMI) was 22.8±3.0 kg/m^2. Based on the FPI score, 146 feet (61.8%) were classified as normal feet, 38 feet (16.1%) were classified as supine feet, and 52 feet (22.0%) were classified as prone feet. There was no significant difference between the three groups for postural sway velocity on US-EO condition. Highest postural sway velocity was detected in individuals with prone feet (6.42±3.81 degree/second, $p=0.003$), followed by those of with normal feet (5.66±3.50 degree/second, $p=0.019$) in the US-EC condition. Individuals with supine feet showed lowest postural sway velocity (3.96±2.52 degree/second). The results of ANOVA are shown in Table I. Linear regression analysis showed that no variable remained in the regression model for US-EO condition. A total of 12 variables were narrowed to three for US-EC condition based on a significance level of $p<0.05$ to enter the model and a $p>0.06$ was the criterion for removal. The resulting three-variable model ($F=8.77$; $p<0.001$; Table II) had an $R=0.32$ and $R2=0.10$ and variance inflation factor (VIF) <2.0 (Table II). Ten percent of the postural sway velocity in the US-EC condition was attributable to all variables in the final model. As the single variable, FPI contributed the greatest relative postural sway velocity ($\beta= 0.246$, $p<0.001$) in the US-EC condition. Hind foot-force time area integral (HF-FTAI) was the only plantar pressure variable that remained in the final regression model contributing to postural sway velocity in US-EC condition ($\beta= -0.127$, $p=0.048$). The SFS also contributed to postural sway velocity ($\beta= 0.141$, $p=0.028$). The results of the multiple linear regression analysis are tabulated in Table II.

TABLE II

Regression results for predicting postural sway velocity from plantar pressure, foot posture index and during the single leg stance

Dependents	Predictors	Mean±SD	B (95% CI)	β	*p*	VIF
Sway velocity (US-EO)						
(degree/second)	Constant	NA	1.004 (0.901, 1.108)	NA	0.000**	NA
	None					
Sway velocity (US-EC)						
(degree/second)	Constant	NA	11.526 (2.7361, 20.691)	NA	0.014*	NA
	FPI	3.60±4.37	0.198 (0.098, 0.297)	0.246	0.000**	1.022
	HF-FTAI (Ns/cm^2)	3.90±0.97	0.509 (0.056, 0.962)	0.141	0.028*	1.048
	SFS	0.38±0.019	-23.104 (-45.998, -0.210)	-0.127	0.048*	1.047

SD: Standart deviation; VIF: Variance inflation factor; * Significant at 0.05 level (two tail); NA: Not applicable; ** Significant at 0.001 level (two tail); US-EC (F=8.77, p<0.001, R=0.32, R2=0.10); US-EO: Unilateral stance eyes open; US-EC: Unilateral stance eyes closed; HF: Hind foot; FTAI: force time area integral; SFS: Standardized foot size; FPI: Foot posture index.

DISCUSSION

To provide information regarding potential impairments of the foot and its disorders, plantar pressure measurements have been demonstrated to be a reliable source that has long been used.[13,14] Although peak pressure and pressure-time integral have widely been used to identify plantar pressure characteristics in the foot,[15,16] these variables exerted by Novel software (Novel, Germany) have not been considered in the current study because they have not been able to give sufficient information on mechanical loading of the plantar surface of the foot. Instead, we used the alternative plantar pressure variable which was described by Melai et al.[12] Whilst information provided by the sole of the foot that is necessary for maintaining postural stability, the plantar pressure characteristics must accurately be measured to obtain the cumulative value. Hence, to provide a measure of the cumulative load on the corresponding area, we divided the FTI of a certain region by the contact area of that region (FTAI, Ns/cm^2) to obtain more accurate mean cumulative load per square centimeter as has been described.[12]

As the debate continues on the validity of the various assessment methods, FPI provides useful indirect information about foot posture. It can therefore be assumed that the plantar contact area increases if the medial arch height decreases in prone feet with high FPI score.[8] In contrast, plantar contact area decreases when medial arch height increases in supinated feet with low FPI score. Standardized foot size was also reported to give more accurate information than width or length alone, hence, it was calculated as foot width divided by foot length as described elsewhere.[17]

As the contributing factor, increase in FPI leads to higher postural sway velocity. Other findings from the regression analysis in the current study are about decreased postural sway velocity in increased SFS. Hence, postural sway control becomes easier as a wider foot provides a larger support surface on unilateral stance. Hind foot-force time area integral was the only plantar pressure variable that remained in the final regression model. Therefore it contributed to postural sway velocity in US-EC condition. Regression analysis showed that postural sway velocity tends to increase if HF-FTAI increases in supine feet, which is opposite that of increasing postural sway velocity in prone feet. This may be because plantar pressure parameters were measured in a dynamic condition, and these differences in force and pressure distributions may demonstrate different strategies to receive ground reaction force during heel strike.

Whilst controversy regarding the effect of foot posture on balance measures has previously been demonstrated,[1,2,6] our findings revealed that the prone feet have increased sway velocity of COG in the US-EC condition. In one of the three studies,[6] a balance test with compliant surface resulted in increased COG sway velocity in young children with feet with less plantar contact to the supporting surface. A second study has also suggested that feet with less plantar contact area have larger COG sway because of absence of medial block, or less plantar cutaneous sensory information.[1] Contrary to this, a recent study showed that participants exhibiting pronated foot postures also achieved poorer performance in postural sway control.[7]

Despite the explained underlying mechanism that is heavily debated, our findings revealed that static balance is largely influenced by mechanical and structural characteristics of the foot alongside the altered sensorial information from two aspects: First, a pronated foot has no sufficient mechanical advantage for proper weight bearing, and stability of the joints therefore could not be provided as suggested by Cote et al.[2] Second, it is reasonable to consider that small alterations to the foot structure or to the bony alignment between foot and ankle could influence postural control strategies; The normal foot can adequately react and neutralize the forces produced from the changes in body sway during posture correction on time before moving the COG away from its normal location. However, the prone foot is unable to respond at the exact time to the load changes during posture control, and also unable to produce a rigid lever arm to generate sufficient counterforce to keep COG on its location. It is well known that when visual input is occluded, the cutaneous receptors and proprioceptors in the foot that process transferring of information must be more reliable for appropriate reactions enabling correct body orientation in space and maintaining balance.[18] If false posture is erroneously perceived to be correct, it probably will result in irrelevant motor responses to correct body orientation in space.[19] Hence, even if more sensorial information is received from the plantar surface in prone feet as suggested, adaptation to false sensorial inputs regarding the current foot posture, and inability to produce a rigid lever arm when it necessary to generate sufficient counterforce may lead higher postural sway velocity in US-EC condition.

In conclusion, postural sway velocity was predicted by only HF-FTAI among the plantar pressure variables in the US-EC condition in the current study. In addition, SFS also weakly predicted postural sway velocity in the same condition. Foot posture index was the main predictor of postural sway velocity. With higher FPI, the group with prone feet demonstrated the greater postural sway velocity. These relationships may suggest important patterns of postural sway velocity in different foot postures and plantar pressures that could be clinically meaningful for improvement of postural stability using effective interventions such as orthosis prescribed for abnormal foot posture, and balance training. However, further studies of different foot postures is still warranted to find out underlying neural and mechanical factors in postural control strategies.

Declaration of conflicting interests

The authors declared no conflicts of interest with respect to the authorship and/or publication of this article.

Funding

The authors received no financial support for the research and/or authorship of this article.

REFERENCES

1. Hertel J, Gay MR, Denegar CR. Differences in Postural Control During Single-Leg Stance Among Healthy Individuals With Different Foot Types. J Athl Train 2002;37:129-132.
2. Cote KP, Brunet ME, Gansneder BM, Shultz SJ. Effects of Pronated and Supinated Foot Postures on Static and Dynamic Postural Stability. J Athl Train 2005;40:41-46.
3. Shumway-Cook A, Horak FB. Assessing the influence of sensory interaction of balance. Suggestion from the field. Phys Ther 1986;66:1548-50.
4. Jonely H, Brismée JM, Sizer PS Jr, James CR. Relationships between clinical measures of static foot posture and plantar pressure during static standing and walking. Clin Biomech (Bristol, Avon) 2011;26:873-9.
5. Ledoux WR, Hillstrom HJ. The distributed plantar vertical force of neutrally aligned and pes planus feet. Gait Posture 2002;15:1-9.
6. Lin CH, Lee HY, Chen JJ, Lee HM, Kuo MD. Development of a quantitative assessment system for correlation analysis of footprint parameters to postural control in children. Physiol Meas 2006;27:119-30.
7. Spink MJ, Fotoohabadi MR, Wee E, Hill KD, Lord SR, Menz HB. Foot and ankle strength, range of motion, posture, and deformity are associated with balance and functional ability in older adults. Arch Phys Med Rehabil 2011;92:68-75.
8. Redmond AC, Crosbie J, Ouvrier RA. Development and validation of a novel rating system for scoring standing foot posture: the Foot Posture Index. Clin Biomech (Bristol, Avon) 2006;21:89-98.
9. Bakirhan S, Angin S, Karatosun V, Unver B, Günal I. A comparison of static and dynamic balance in patients with unilateral and bilateral total knee arthroplasty. Eklem Hastalik Cerrahisi 2009;20:93-101.
10. Bakırhan S, Unver B, Karatosun V. Investigation of body weight ratios on joint structures at different knee flexion angles in patients with unilateral knee arthroplasty. [Article in Turkish] Eklem Hastalik Cerrahisi 2013;24:7-11.
11. Mickle KJ, Munro BJ, Lord SR, Menz HB, Steele JR. Gait, balance and plantar pressures in older people with toe deformities. Gait Posture 2011;34:347-51.
12. Melai T, IJzerman TH, Schaper NC, de Lange TL, Willems PJ, Meijer K, et al. Calculation of plantar pressure time integral, an alternative approach. Gait Posture 2011;34:379-83.
13. Fitzgerald RH, Vedpathak A. Plantar pressure distribution in a hyperpronated foot before and after intervention with an extraosseous talotarsal stabilization device-a retrospective study. J Foot Ankle Surg 2013;52:432-43.
14. Ateşalp S, Demiralp B, Ozkal UB, Uğurlu M, Bozkurt M, Başbozkurt M. Modified Evans technique improves plantar pressure distribution in lateral ankle instability. Eklem Hastalik Cerrahisi 2009;20:41-6.
15. Arnold JB, Causby R, Pod GD, Jones S. The impact of increasing body mass on peak and mean plantar pressure in asymptomatic adult subjects during walking. Diabet Foot Ankle 2010;1.
16. Aminian G, Safaeepour Z, Farhoodi M, Pezeshk AF, Saeedi H, Majddoleslam B. The effect of prefabricated and proprioceptive foot orthoses on plantar pressure distribution in patients with flexible flatfoot during walking. Prosthet Orthot Int 2013;37:227-32.
17. Morse SA, Bennett MR, Liutkus-Pierce C, Thackeray F, McClymont J, Savage R, et al. Holocene footprints in Namibia: the influence of substrate on footprint variability. Am J Phys Anthropol 2013;151:265-79.
18. Famuła A, Nowotny-Czupryna O, Brzek A, Nowotny J, Kita B. Telereceptive and proprioceptive control of balance vs. body stability in elderly people. Ortop Traumatol Rehabil 2008;10:384-95.
19. Cakrt O, Slabý K, Viktorinová L, Kolář P, Jeřábek J. Subjective visual vertical in patients with idiopatic scoliosis. J Vestib Res 2011;21:161-5.