Original Article

Nonlinear analysis of postural sway in subjects with below knee amputation during opened and closed eye conditions

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ABSTRACT

Objective: The aim of this study was to compare the structure of postural sway in healthy people and amputees with SACH foot (solid ankle cushion heel) and single axis foot during standing.

Methods: Twenty healthy, 10 amputees with single axis foot, and 10 amputees with SACH foot participated in this study. The structure of postural sway of the subjects was evaluated using approximate entropy (ApEn).

Results: People with SACH foot prosthesis exhibit increased regularity in postural sway compared to healthy people and people with single axis foot.

Conclusion: Amputees who used single axis prosthesis achieved appropriate adaptation to their prosthesis device.

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1. Introduction

Lower limb amputations are performed as a result of trauma, vascular disease, diabetes, cancer, congenital disorders, and surgery.^{1–3} It has been shown that the incidence of amputation varies between 2.8 and 43.9 per 100,000 in the United States, in which 43% are transtibial,⁴ 24% through knee, and 29% are above knee.^{1,3} Various types of prostheses have been designed to improve the abilities of the subjects to stand and walk independently. The performance of subjects can be represented as stability during standing and ability to walk efficiently during walking with less energy expenditure. It has been defined that stability is the ability of subjects to return their body from an unstable to a stable position.⁵ Ideal postural control depends on appropriate performance of various parts of musculoskeletal system and integrity between sensory and mobility parts.^{5–9} Sensory information from interoceptors and exteroceptors in body give information about the position of different parts of the body related to each other and also position of body in relation to the environment.^{4,8} Subjects with below knee amputation miss ankle strategy, which is one of the effective strategies to control and restore the stability during

standing and walking.¹⁰ Moreover, they miss the proprioception inputs from sensory receptors of ankle and foot.^{7,9} Therefore, they need to compensate the loss of input information by use of visual inputs.

There are many approaches to assess the postural stability, in which, one of them is investigation of postural sway with force plate. Examination of stability based on postural sways can be done by use of linear and nonlinear approaches. Linear method of postural control evaluation, such as COP (center of pressure) excursion, velocity of COP sway, and path length of COP sways, have being used in different studies of postural control investigation.^{11,12} Linear method only focuses on quality of stability.^{13,14} In contrast, nonlinear method, such as approximate entropy (ApEn), has been used to quantify quite standing COP variability. It means that it gives insight about behaviors of postural sway during the time.^{14,15} Recently, some authors employed nonlinear analyzing approaches, such as approximate entropy in their studies. For example, in one study, pattern of postural sway was investigated in patients with multiple sclerosis by approximate entropy. In another study, Cavanaugh et al. explored the effect of cognitive task on behavior of postural sway in healthy young adults. There are also other studies that used approximate entropy in analyzing pattern of postural sway in their studies.

Stability of below knee amputees has been investigated in a few studies based on questionnaire or use of linear approaches.^{16–19} However, it was not clear whether the structure of postural sway of amputees differs from that of normal subjects or not. Analyzing

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postural sway in people with the below knee amputees using nonlinear approaches may clarify that exactly what differences in structure of postural sway exists in the people with amputees in comparison to the healthy people. Moreover, there were no enough evidences regarding the influences of vision on pattern of postural sway of amputees. Therefore, the first aim of this study was to investigate the behavior of postural sway of below knee amputees by use of nonlinear approach and to determine the effects of vision on their pattern of standing stability. The main hypothesis associated with this study was that the structure of postural sway in the people with below knee amputees was the same as that of normal subjects and lack of vision does not influence on their structure of standing sway.

In addition, two types of prostheses are commonly used by people with below knee amputees (SACH foot and single axis foot prosthesis). Second purpose of this study was to examine what structural differences may exist in pattern of postural sway between amputees who used SACH foot and single axis foot prosthesis.

2. Methods

2.1. Subject

A total of 20 healthy and 20 amputee subjects were recruited to participate in this study. Subjects were matched based on age, height, weight, and gender (Table 1). An ethical approval was obtained from Shahid Beheshti University of medical sciences ethical committee. The main inclusion criteria for amputees were who had below knee amputation for more than 2 years and were using current prosthesis for more than 6 months. The amputees were divided into two groups, including, those who use single axis foot and those who used SACH foot. The main inclusion criteria for healthy people were those people who had no musculoskeletal, neurological, psychological, and immunological illness.

2.2. Data recording

For postural sway (COP) recording, a Kistler force plate platform (50 cm × 60 cm) was employed. Data recording was performed at frequency of 120 Hz. The subjects were asked to stand upright on the force plate with open and then closed eyes. The duration of each trial test was 60 s. Each opened and closed eyes condition test was performed in 5 trials. The first and last 15 s of the data were deleted and only 30 s of data were used for final analysis. So, we had 3600 data points. In other studies, less than 3600 data points were used.^{20,21} The data analyzed unfiltered, so that the data dynamic properties stay unchanged.

2.3. Data analyzing

The pattern of postural stability of the subjects was evaluated by the nonlinear analysis method. Approximate entropy (ApEn) parameter was used to evaluate dynamic pattern of standing sway.¹⁵ The values of ApEn range from 0 to 2. Smaller values reveal that sequence was repeated regularly, while higher values will show that sequence was repeated randomly.²²

The mathematical method used to calculate ApEn was the one used by Pincus and Kalman.^{23–25}

Here, the ApEn was defined as $ApEn(m, r, N)$, in which m is the length of compared runs, r is a tolerance, and N is input data points. The procedure of calculating ApEn is as follows:

Given a time series of data $u(1), u(2), \dots, u(N)$ from measurements form a sequence of vectors: $x(1), x(2), \dots, x(N - m + 1)$ in R^m , defined by $x(i) = [u(i), u(i + 1), \dots, u(i + m - 1)]$.

Define for each $i, 1 \leq i \leq N - m + 1$:

$$C_i^m(r) = \frac{\text{number of } j \text{ such that } d[x(i), x(j)] \leq r}{N - m + 1} \quad (1)$$

where

$$d[x(i), x(j)] = \max(|u(i+k-1) - u(j+k-1)|), \quad k = 1, 2, \dots, m \quad (2)$$

$$\text{Define: } \Phi^m(r) = \frac{1}{N - m + 1} \sum_{i=1}^{N - m + 1} \log C_i^m(r) \quad (3)$$

Then:

$$ApEn(m, r, N) = \Phi^m(r) - \Phi^{m+1}(r) \quad (4)$$

2.4. Statistical analyses

All statistical analyses were conducted by software of SPSS 20.0. Normal distribution of the parameter was evaluated using the Shapiro–Wilk test with a significant point at 0.05. A separate 2×2 repeated measures ANOVA model was used to test for effects of GROUP (amputees vs. control) and CONDITION (eyes open vs. closed), and interactions of these factors between normal group and total amputee group. In addition, a separate 3×2 repeated measures ANOVA model was conducted to test for effects of GROUP (control, SACH foot, and single axis foot), CONDITION (eyes opened vs. closed) and interactions of these factors. Alpha was set at 0.05 for all statistical analyses.

3. Results

Table 2 shows the mean and SD of the ApEn variables for different conditions of postural in each participated group.

Table 3 shows that, when we considered total amputees as a group and normal subjects as another group, the main effect for condition of test was significant only in AP direction ($F = 19.8, p = 0.00$). But the group and interaction between group and condition had no significant effect on any variable. In ML direction, no significant effect of group, condition, and interaction between group and condition was observed.

Table 3 shows the main effect of group, condition, and interaction between group and condition when we classified amputee subjects in two separate groups, single axis foot, and SACH foot group, and normal subjects as an another group. Based on these results, in AP direction, all variables had significant effect on values of ApEn ($p = 0.00$). But, group had only significant variables that had main effect in ML direction ($F = 1.7, p = 0.00$). The results of post hoc multiple comparisons showed that amputees with SACH foot had the values of ApEn in AP and ML direction that was significantly less than other two groups ($p < 0.05$).

Table 1

The characteristics of subjects that participated in this study.

Participants				Number	Age	Mass	Height
Amputees group	Type of foot 10 SACH foot 10 single axis foot	Cause of amputation Trauma	Socket system PTB	20	50 ± 5	61 ± 12.5	1.7 ± 0.15
Control group				20	45 ± 7	58 ± 7.5	1.65 ± 0.12

Table 2

Descriptive data (mean and standard deviation) of ApEn variables in open and closes eye conditions for groups.

Independent variables		Test condition			
		Opened eyes (Mean $\pm$ SD)		Closed eyes (Mean $\pm$ SD)	
		AP	ML	AP	ML
Descriptive data	Normal	0.65 $\pm$ 0.12	0.66 $\pm$ 0.14	0.70 $\pm$ 0.11	0.68 $\pm$ 0.13
	Amputees with single axis foot	0.70 $\pm$ 0.12	0.74 $\pm$ 0.16	0.73 $\pm$ 0.12	0.73 $\pm$ 0.19
	Amputees with such foot	0.53 $\pm$ 0.07	0.48 $\pm$ 0.12	0.64 $\pm$ 0.10	0.51 $\pm$ 0.19
	Total amputees subjects	0.61 $\pm$ 0.14	0.61 $\pm$ 0.20	0.69 $\pm$ 0.12	0.62 $\pm$ 0.22

Table 3Statistical analysis of *F* ratios and *p*-values by ApEn variables. Significant differences (*p* < 0.05) are in bold.

Groups	Main effect	Direction			
		AP		ML	
		<i>F</i>	<i>p</i>	<i>F</i>	<i>p</i>
Normal, such foot, single axis foot	Group	8.5	0.00	12.7	0.00
	Condition	38.2	0.00	0.45	0.51
	Group $\times$ condition	6.19	0.00	1.07	0.35
Normal, total amputees	Group	0.52	0.48	1.1	0.3
	Condition	19.8	0.00	0.48	0.49
	Group $\times$ condition	0.52	0.48	0.15	0.69

Fig. 1. ApEn values in AP direction.

Figs. 1 and 2 show the COP patterns of amputee with SACH foot, amputees with single axis foot, and normal subjects in eyes opened and closed conditions in AP and ML direction, respectively. Figs. 3 and 4 show the COP patterns postural sway in total amputees and normal subjects in eyes opened and closed conditions in AP and ML direction, respectively.

4. Discussion

Those with lower limb amputation miss some strategies that require to control standing stability and also the mechanoreceptors located in skin and joints depend on level of amputation.^{26–29} It seems that the foot components influence standing stability. However, there was not enough evidence in literature to show the effects of amputation in below knee amputees and also type of prosthesis components on their pattern of COP standing stability during open and closed eyes conditions. Therefore, the first aim of this study was to evaluate the difference between stability of normal subjects and amputees. Moreover, it was aimed to

investigate the difference in pattern of postural sway of amputees with SACH and single axis foot during opened and closed eyes conditions in comparison to healthy people.

We used ApEn as a tool for evaluating structure of postural sway during quite standing. Approximate entropy represents the regularity of a system. The lower value of ApEn is concluded as regularity of the system and ability of body to stabilize center of gravity during standing position,^{14,25} while its upper values represent that a data time series is repeated randomly.²²

Fig. 2. ApEn values in ML direction.

Fig. 3. ApEn values in AP direction.

The results of current study showed that when we evaluated cop time series between a pooled population of people with below knee amputation, without regarding their prosthesis device, and healthy people no significant difference was found in AP and ML postural sway between the two groups. From open eyes to closed eyes condition, two groups exhibited more randomly postural sway in their standing task. Therefore, the pattern of postural sway in the pooled amputees group was same as healthy group during open and closed eyes standing tasks.

But as amputees, people were classified in two groups based on their prosthesis type; different results were obtained. As the results showed, during standing in opened eye condition, people with SACH foot prosthesis had lesser ApEn and more regularity in cop sway pattern than healthy people and people with single axis foot prosthesis in AP direction. Also, as the task became more difficult from open to closed eyes condition, postural sway in the 3 participated groups became more random. Effect of group $\times$ condition in AP direction was significant. In ML direction, such as AP direction, SACH foot amputees group exhibited more regularity in their postural sway. But, from open to closed eyes condition, no significant effect was observed in the variables.

The increased regularity in pattern of postural sway in the amputees with SACH foot prosthesis was consistent with pattern, which was observed in other patient groups, such as multiple sclerosis, athletes with a history of cerebral concussion and Ehlers–Danlos syndrome.^{20,30,31} Some authors proposed that more regularity in postural sway in patient groups is a reason for their difficulty to maintain upright balance.^{20,30,31} Decreased values of ApEn in amputees with SACH foot prosthesis indicate that they had less divergence and more predictable postural sway than healthy people. The changed postural sway in amputees with SACH foot prosthesis could indicate that they have less adaptability to respond to perturbations in different task and environment.

But, when we compared COP time series in AP and ML directions between control and amputees with single axis foot prosthesis, no significant differences were observed between two groups.

The main reasons for the results of postural sway, which were seen in amputees with single axis foot prosthesis, may be due to appropriate alignment of their prosthesis components^{26,32} and their adaptation to prosthesis. The foot of prosthesis was aligned in some degrees of dorsiflexion.³³ Based on the results of various research studies, this posture improves standing stability.^{26,32} The lack of proprioception and sensory inputs of foot and ankle joint was compensated by skin, which is in contact with the socket and also may be the vision, which is important especially after amputation.^{7,9,34}

It has been shown that during the first year of amputation, amputees depend upon their vision to improve their standing.⁹ However, their dependency on vision decrease after the first year of amputation.⁹ Therefore, it may be that amputees with single axis foot have the same abilities as normal subjects to stand efficiently due to appropriate alignment of prosthesis components and also good proprioception of skin that is in contact with socket, which works as a sensory inputs source. The results of our study demonstrated that amputees with single axis prosthesis in comparison to amputees with SACH foot prosthesis adapted to prosthesis device. In addition, based on the results of this research, below knee amputees with single foot have a neuromuscular system, which responds to environment stimulation properly, and can adapt their balance during standing the same as normal subjects. So, single axis foot type of prosthesis may be proper than SACH foot prosthesis type for people with below knee amputees.

The results of this research can be used by clinician to prescribe appropriate foot for below knee amputees depending on their age and also their muscular strength. The results of this study

confirmed that those subjects who used SACH foot have more regularity and therefore less ability to control their postural balance. It means that their stability during standing is mostly controlled by stiffness of prosthesis foot keel (a segment inside foot). So, they are stable as much as the stiffness of prosthesis foot can control the sway. Therefore, it is recommended that this type of prosthesis foot be used especially for elderly subjects, as the stiffness of the foot improves their stability. In contrast, young amputees are advised to use single axis foot, as they are able to control their stability with muscular forces of knee and hip joints. Use of this kind of foot improves their walking performance. There is no doubt that based on various research studies the association between static and dynamic balance is not too high. It means that the ability of a subject to improve the static balance does not reflect his or her ability to improve dynamic stability. However, in most of the studies, the static stability has been evaluated on linear approach. Moreover, in most of them, dynamic stability has been evaluated based on hand tasks or other tests. In contrast, in the current study, the stability is evaluated based on nonlinear approach, which determine the ability of neuromuscular system to response to the changes of environment. However, it is recommended that in future studies dynamic stability will be evaluated during walking.

4.1. Limitation

Because we evaluated pattern of balance control only during standing task, it is not clear what pattern of balance control may exist during dynamic task, such as gait in each group. In addition, cognition task can influence pattern of postural sway. It is recommended that in future studies the effect of cognition task on balance control of people with below knee amputees with different types of prosthesis investigated. Another limitation of this study was that only two types of feet were investigated. Therefore, it is recommended that the stability of amputees be investigated with different types of foot in further studies. Another limitation of our study was limited participation in the groups with amputation.

5. Conclusion

Pattern of postural sway of the heterogeneous amputees with different types of prosthesis during standing with eyes opened and closed was the same as the normal subjects. But, when we classified amputees in heterogeneous subgroup, based on their prosthesis type, people who used SACH foot prosthesis exhibited more regularity in their postural sway. Therefore, people who use SACH foot prosthesis may have less ability to control their postural balance during standing.

Conflict of interest

The authors report no conflicts of interest. The authors alone are responsible for the content and writing of the article.

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