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Original Article

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

Meissam Sadeghisani [a,1], Mohammad Taghi Karimi [b,*], Mostafa Kamali [b]

[a] Physical Therapy Department, Rehabilitation Faculty, Shahid Beheshti University of Medical Sciences, Tehran, Iran
[b] Musculoskeletal Research Center, Rehabilitation Faculty, Isfahan University of Medical Sciences, Iran

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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.

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 introceptors and extroceptors 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

* Corresponding author. Tel.: +98 3117922021.
E-mail addresses: Sadeghi.m@sbmu.ac.ir (M. Sadeghisani), karimi@rehab.mui.ac.ir, mohammad.karimi.bioengineering@gmail.com (M.T. Karimi).
[1] Tel.: +98 9137716567.

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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 $\times$ 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 $u(1)$, $u(2)$, ..., $u(N)$ from measurements form a sequence of vectors: $x(1)$, $x(2)$, ..., $x(N - m \pm 1)$ in R^m, defined by $x(i) = [u(i), u(i \pm 1), \ldots, u(i \pm m - 1)]$.

Define for each i, $1 \le i \le N - m \pm 1$:

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

where

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

$$\text{Define}: \quad \Phi^m(r) = \frac{1}{N - m \pm 1} \sum_{i=1}^{N-m\pm1} \log C_i^m(r) \quad (3)$$

Then:

$$\text{ApEn}(m, r, N) = \Phi^m(r) - \Phi^{m\pm1}(r) \quad (4)$$

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