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The Effect of Phantom Sensation on the Autocorrelation of Gait in Amputation

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***Abstract*—Amputation affects the individual's entire life with a long rehabilitation and adaptation process. Phantom sensation is the sensing of the presence/position of the limb that existed before but subsequently lost its function. Our research aims to investigate the effect of phantom limb sensation on the autocorrelation of gait in individuals with transtibial amputation. In this context, autocorrelation function (ACF), rescaled range analysis (RRA), and power spectrum density (PSD) evaluations are employed to analyze the acceleration data of gait from the vertical plane. Subjects with unilateral trans-tibial amputation and prostheses were involved in the work. As a result, the gait profile of individuals with phantom sensation for approximately 512 steps on a non-perturbed ground is similar to healthy individuals by the results obtained from all three methods. This shows us that phantom sensation can be a functional part of gait and is a supporting factor for amputees in the adaptation process.**

***Keywords*—Amputation, Autocorrelation, Gait, Phantom Sensation, Rehabilitation Engineering**

I. INTRODUCTION

Limb loss is an important event that restricts the individual's functional capacity and leads to considerable financial costs on individuals' social and professional roles [1], [2]. The phantom limb sensation is a complex feeling of an amputated limb and can be observed as a result of an amputated limb is still perceived by the central nervous system [3], [5]. In the presence of phantom sensation, the person feels that the lost limb is still in place, and may declare that he/she has feelings such as itching and tickling, etc. In some cases, a pain, named phantom pain, may be felt in the non-existing limb. In the literature, it was seen that the effect of phantom pain on the functions of individuals was measured by verbal reporting [6]. The existing studies on the gait function of amputated individuals generally focus on the prosthesis or how the person's own physical characteristics affect the time-distance characteristics of gait [7], [8]. However, whether the phantom sensation provides a functional contribution to a complex phenomenon such as walking has not been investigated.

Gait is one of the essential functions of human beings and is an integrated movement that requires the complex interaction of body systems [9], [10]. It hides important key points for physical abilities [11] and neuromotor system organization. The gait pattern of a healthy individual is different from the gait of a person who has any disruption/disorder in body systems. A gait cycle basically begins with the heel of a step contacting the base/ground and ends with the same heel touching the base again [12]. It is formed by the interaction of the biomechanical events of each step with the concepts of time and distance [12], [13]. On the other hand, these time-distance characteristics differ during long gait cycles [9]. Variability in gait is expressed as step-to-step fluctuations throughout the gait cycle.

The term autocorrelation is conceptually the relationship between the values of the signal of a series in any period at different times. The presence of the situation indicates the deviations within the series are not random. The autocorrelation in gait shows consistency and similarity in repeated fluctuations [14], [15]. Even if an autocorrelated gait is variable, it gives important information about neuromotor system consistency.

In the literature, it is seen that the number of studies examining the gait autocorrelation of amputated individuals is limited. These studies mostly examined the autocorrelation of body movements during walking and did not correlate it with any condition (structural, demographic, clinical, etc.) of individuals with amputation. In addition, the gait of these individuals was

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evaluated by cross-sectional analysis, and autocorrelation was calculated by repetitive simulation of the obtained data [16], [17], [18]. Besides the use of autocorrelation function (ACF), rescaled range analysis (RRA) and power spectrum density (PSD) methods are mostly employed as fundamental methods in gait analysis [4], [14], [19], [20].

Investigating the effects of the phantom limb sensation on the autocorrelation of gait in subjects with transtibial amputation was the aim of the study. Subjects with unilateral traumatic transtibial amputation who have phantom sensation without any painful sensation were the study group. Individuals with transtibial amputation without phantom sensation, and healthy subjects were the control groups of the study. Gait analyses were performed on a motorized treadmill by using inertial measurement units at the participant's self-selected speed. Data from at least 512 consecutive steps were used for computations.

Section II introduces data acquisition process and autocorrelation investigation techniques, while Sections III and IV discuss experimental outcomes. Section V presents conclusion and future work.

II. METHODOLOGY

A. Data Acquisition

Subjects with unilateral trans-tibial amputation and prostheses were involved in this work. Amputated subjects were split into two groups as those who felt phantom sensation (Phantom Group, PG) (n = 4) and those who did not feel any phantom sensation (Non-Phantom Group, N-PG) (n = 4). Furthermore, 4 healthy subjects were employed as the control group (HC). It was asked from participants to walk at least 512 steps at their preferred speed through a motorized treadmill on the non-perturbed ground. The gait data were collected using the sensors of the RehaGait-Pro system [3]. Table I gives detailed information about the participants.

TABLE I. Detailed Information About Employed Groups

	The Groups		
	PG	***N-PG***	***HC***
Number of subjects	4	4	4
Gender distribution (F/M)	0/4	1/3	1/3
Age ($\mu \pm \sigma$ years)	34.75 ± 9.9	36.5 ± 8.3	34.9 ± 8.6
Average velocity (m/s)	2.63 ± 0.47	2.16 ± 0.41	3.28 ± 0.56
Average BMI (kg/m^2)	22.6 ± 2.2	22.91 ± 1.8	21.98 ± 2.8

μ: average, σ: standard deviation, F: Female, M: Male

B. Autocorrelation Function (ACF)

The ACF examines the autocorrelation among the univariate time sequences y_t and y_{t+k}, where *k = 0,...,K* and y_t is a random process [21]. The autocorrelation for lag *k* can be calculated as in

$$r_k = \frac{c_k}{c_0}, \tag{1}$$

where c_0 is the sample variance of the time sequence data and c_k is obtained with

$$c_k = \frac{1}{T}\sum_{t=1}^{T-k}(y_t - \overline{y})(y_{t+k} - \overline{y}). \tag{2}$$

C. Rescaled Range Analysis (RRA)

RRA is one of the statistical methods used to analyze trends in time series. This analysis identifies persistence or average reversal trends within the signal. The Hurst exponent (*H*), also called as the "index of dependence" ranges from 0 to 1 and measures randomness. When $H \geq 0.5$, it is expected that the next signal value is likely to be like a data point preceding it. Thus, it can be deduced that the correlation between the signal frames is strong. Conversely, if the $H < 0.5$, then the time series performs a random stochastic process.

D. Power Spectral Density (PSD)

A periodogram is a non-parametric estimation of the PSD of the signals. The periodogram is obtained by the Fourier transform of the ACF. For a signal *x(n)* sampled at a sampling frequency *fs* per unit time, the periodogram is described as:

$$\hat{P}(f) = \frac{\Delta t}{N}\left|\sum_{n=0}^{N-1} x_n e^{-j2\pi f \Delta t n}\right|^2, -1/2\Delta t < f \leq 1/2\Delta t, \tag{3}$$

where Δt is the sampling interval.

III. EXPERIMENTAL RESULTS

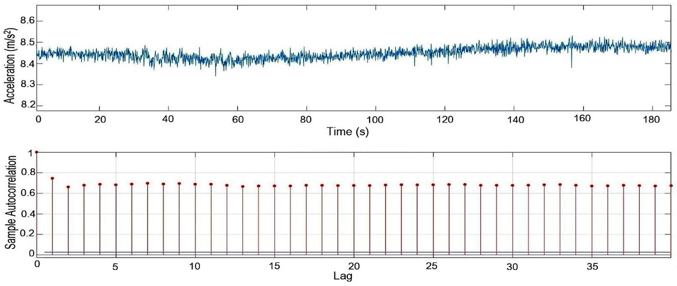
The signal processing applications and calculations on the collected raw data were carried out via MATLAB R2019a. It is known in the literature that acceleration during walking in the vertical plane plays a crucial role in the detection of autocorrelation behavior of signals [22]. For this reason, the acceleration values from the vertical axis were evaluated in this study.

A. Autocorrelation Function Evaluation

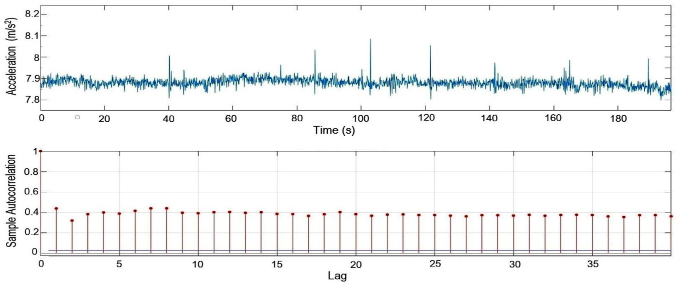
Fig. 1 indicates an example of the application of the autocorrelation function to the PG, N-PG and HC gait signals, respectively. As seen in the graphs, the autocorrelation values of amputee individuals with phantom sensation are higher than those who do not feel within the environment without perturbation, and they show a similar autocorrelation profile with healthy individuals.

B. Rescaled Range Analysis Evaluation

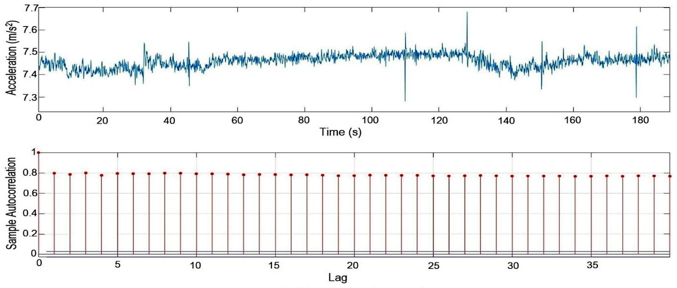
Table II indicates the participant-based Hurst exponential values for each group. When we evaluate the results individually, it can be seen that amputees participants with and without phantom sensation achieved the H-value above the 0.5 threshold. This means that the steps taken by amputees during walking are correlated with each other, and deviations and differentiation from the normal order of walking are low. Furthermore, when the results are compared on a group basis, it was observed that individuals who do not have phantom sensation have a lower H value than the HC and PG. However, individuals in PG have obtained closer values to the results of healthy individuals. Considering the results, it can be concluded that phantom sensation supports amputees to exhibit a similar gait profile to a healthy individual during walking on the non-perturbed ground.



(a) Amputation with Phantom sensation

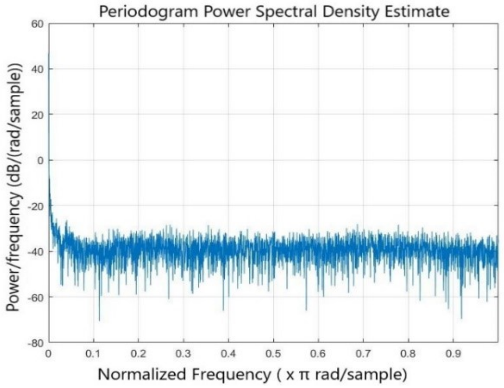


(b) Amputation without Phantom sensation

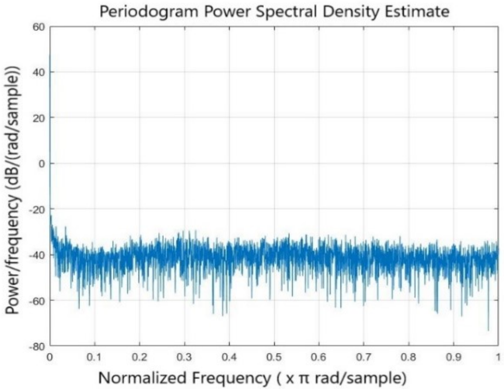


(c) Healthy Control

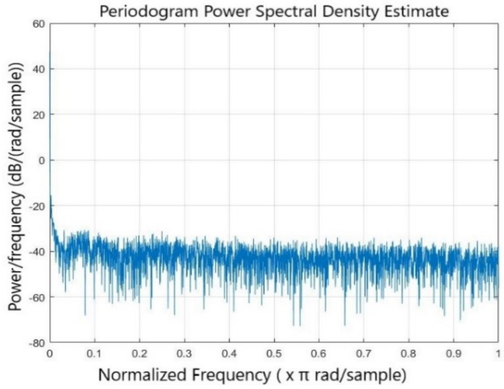
Fig. 1. Autocorrelation function graphics for (a) Amputation with Phantom sensation, (b) Amputation without Phantom sensation and (c) Healthy control. The values in the graphics represent the average outcomes for relevant groups of subjects.



(a) Amputation with Phantom sensation



(b) Amputation without Phantom sensation



(c) Healthy Control

Fig. 2. Periodograms of PSD estimations for (a) Amputation with Phantom sensation, (b) Amputation without Phantom sensation and (c) Healthy control. The values in the graphics represent the average outcomes for relevant groups of subjects.

C. Power Spectral Density Evaluation

Before calculating the PSD, the fast Fourier transform was applied to the signals to convert the signal from the time domain to the frequency domain. To obtain the PSD of a signal by the periodogram method, the signal is divided into frames as the power of 2 (i.e. 64, 128, and 256). In this method, the data is divided into overlapped segments and the mean of the Fourier transform of each segment is employed to compute the PSD estimation. In this study, the signals obtained from the participants were approximately 240 seconds, and the sampling frequency was chosen as 256 Hz in order to extract the power spectrum density. Fig. 2 represents the periodograms of average PSD estimations for PG, N-PG, and HC groups, respectively.

TABLE II. HURST EXPONENT VALUES OF RRA FOR EACH PARTICIPANT

Subject Number	**The Groups**		
	PG	***N-PG***	***HC***
Subject 1	0.952	0.771	0.896
Subject 2	0.891	0.859	0.959
Subject 3	0.915	0.770	0.970
Subject 4	0.938	0.814	0.910

From the visual results of PSD, it can be deduced that the phantom sensation provides a healthy gait function to the person during mobility. Amputees without phantom sensation perform more fluctuations, differences, and lower self-periodicity values while moving. In addition to the figures, the mean frequency densities of the PG, N-PG, and HC groups are calculated. The individuals of the PG and HC groups obtained similar frequency densities, indicating that they exhibited similar gait profiles.

In addition, we analyzed our findings with a proper statistical test to assert the differences between the groups. Mann Whitney U test was performed due to non-parametric test conditions. According to the test evaluation, the results of the PG and HC were similar ($p > 0.05$). It was determined that there was a difference in the N-PG group according to the RRA ($p = 0.029$) and PSD ($p = 0.029$) methods. The results showed that the Phantom sensation provided better gait autocorrelation in amputees.

IV. DISCUSSION

Autocorrelation analysis in gait provides distinctive information about whether the problem observed in gait is due to peripheral factors or the central nervous system. It is necessary to investigate the presence of autocorrelation in order to measure the contribution of a sensation associated with the central system, such as phantom sensation, to the function. If the gait shows an autocorrelated structure, it will be expected that any series taken from the signal is similar to the entire signal.

As can be seen in the graphs of autocorrelation functions, it can be concluded that the irregularities that may disrupt the harmony of the signal during walking are tolerated more quickly in healthy and phantom-feeling individuals than in other amputees, and tends to the normal gait profile.

V. CONCLUSIONS AND FUTURE WORK

In this paper, preliminary experimental results of an ongoing scientific research project were represented. A gait with autocorrelation demonstrates the smoothness of the interaction of the neuromotor system functions with the peripheral system. Thus, it can be determined whether the phantom sensation provides an advantage in terms of gait function. The results provide valuable information, especially in terms of amputee rehabilitation and will serve as a guide for amputee rehabilitation.

In the literature, autocorrelation function, rescaled range analysis, and power spectrum density methods are mostly employed as baseline methods in gait analysis. To the best of our knowledge, there are not many studies that examine the effect of phantom sensation for amputee individuals during movement. We believe that this study will be one of the pioneering works to enlighten this phenomenon.

There are also some limitations of this study. First of all, it is planned to make more generalizable inferences by increasing the number of participants. There are many factors that need to be examined, such as the irregularity of the gait, its fractality, and the adaptation processes in different situations in future works.

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