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Utilizing Cross-Correlation to Determine Phase Shift in Gait Data for a Neural Prosthesis

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INTRODUCTION

According to the PEW Research Center, nearly 40 million people in the US live with a disability. This number represents approximately 1/8 of the population. There are many reasons that people have disabilities and some people may be helped by innovative medical devices.

To address this need, our research group is developing a neural prosthesis to assist people with muscle weakness caused by injury or disease. The device is designed to monitor movement during gait and artificially stimulate the gastrocnemius muscle at the appropriate time in the gait cycle to enhance plantar flexion to improve gait. Because people change their gait during normal movement activities, the task of determining the current position in the gait cycle in not trivial. Our third-generation neural prosthesis utilizes inertial measurement units (IMUs) attached to the foot, shank, thigh, and pelvis. Each IMU has a triaxial accelerometer and a triaxial gyroscope to monitor the direction of the gravitational force vector and the angular velocity, respectively. These sensors are used to determine the segment angles with respect to the global reference frame and through calculation, the joint angles can be determined. The neural prosthesis also utilizes foot pressure sensors to provide additional information about the gait of the user. These sensors are accessed by an integrated computer within the neural prosthesis for real-time analysis of gait. However, it is not known how accurately the IMUs and foot pressure sensors can detect actual gait characteristics.

The gold standard for measuring human movement are multi-camera systems that utilize body markers to detect movement. These camera systems have proven to be accurate and will be used as a reference for measuring the accuracy of the IMUs in the neural prosthesis. The low cost IMUs (about $5.00 US) are expected to be less accurate than the camera system (about $500k US). However, the accuracy may still be sufficient to accurately determine the phase of the gait cycle. This study was designed to determine the sensitivity of the system to measurement error. Mathematical analysis of human movement patterns were performed to determine the sensitivity of using the cross-correlation function to accurately detect phase shift in the presence of different levels of noise.

METHODS

An able-bodied individual was recruited to participate in the gait study. After being explained the nature of the study and signing the informed consent form approved by the IRB, reflective markers were placed on the lower body. The participant walked in a straight line over level ground while a camera system captured her movement.

These data were processed to determine joint angles and ground force reactions. These data sets were imported into a custom MATLAB code for data analysis. Gaussian random noise was added to the signal to simulate errors in the IMU's ability to accurately detect the exact joint angles. The probability density function is given by,

$$y(x) = \frac{1}{\sigma\sqrt{2\pi}}\, e^{\frac{-(x-\mu)^2}{2\sigma^2}} \qquad (1)$$

where, μ is the mean, and σ is the standard deviation. In our case μ was zero, and σ was one, so the equation simplified to,

$$y(x) = \frac{1}{\sqrt{2\pi}}\, e^{-\frac{1}{2}x^2} \qquad (2)$$

A random number generator within MATLAB was used to generate Gaussian random values with a root mean squared (rms) magnitude of one. These random values were multiplied by a noise level between 0.01 and 10 to scale the noise added to the original signal so that the effect of different levels of noise could be evaluated.

In order to comparing the data collected by the IMUs with camera system data, the data collected by the two separate systems would need to be synchronized. Asynchronous data was simulated by randomly phase shifting two noisy gait cycle data sets between a range of 0 to 300. These data sets were analyzed using a cross correlation function to determine the phase shift between the two data sets,

$$(f \star g)(\tau) \stackrel{\text{def}}{=} \int_{-\infty}^{\infty} f^*(t)\, g(t+\tau)\, dt \qquad (3)$$

where, f and g are the two randomly shifted signals, τ is the time shift and t is time. The cross-correlation function is maximized when the two signals are best aligned and the values of τ can be determined.

Finally, the effect of noise levels ranging from 0.01 to 10 degrees rms at 0.01 degree intervals was evaluated. Each of the 1000 different noise levels was evaluated 200 times and the ability of the cross-correlation function to accurately determine the actual phase shift was determined as a function of noise level.

RESULTS

Joint angles collected using the camera system from a single gait cycle of a typical able-bodied individual are shown below (Figure 1). The results also show that a low noise level generally follows the original gait shape.

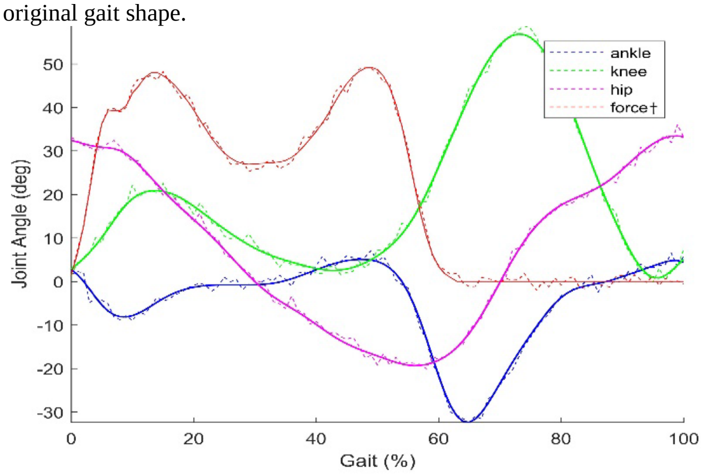
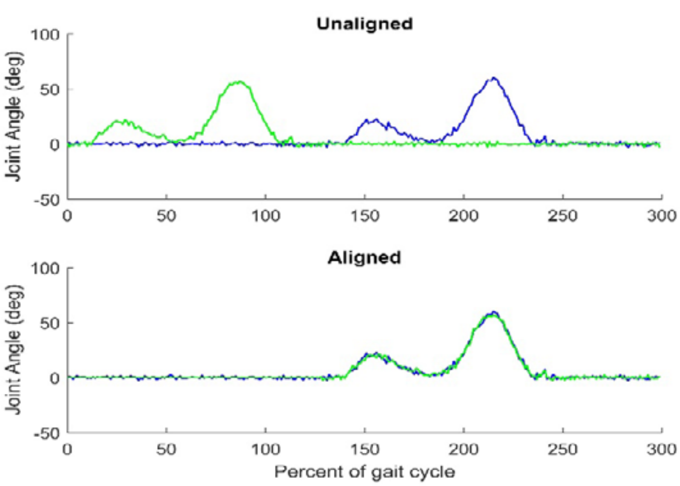


Figure 1: Natural joint angles during gait (solid lines) and gait perturbed by Gaussian random noise at one degree rms (dashed lines). †The normalized force has units of Newtons/20.

Evaluation of two randomly shifted knee joint angles, with one degree rms of noise are shown before and after synchronization (Figure 2a). The method is also able to synchronize the signals the high noise levels, ten degree rms (Figure 2b).

a)



b)

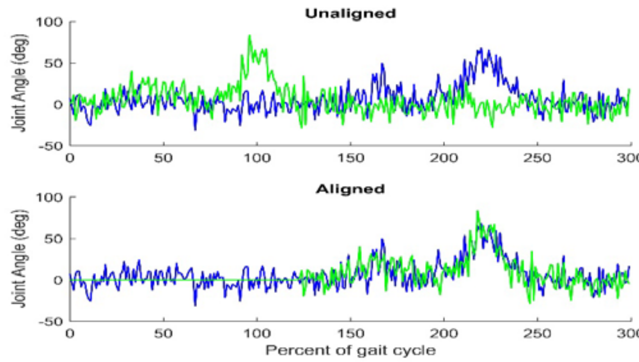


Figure 2: Synchronization of signals using the cross-correlation function at two noise levels, (a) one and (b) ten degrees rms.

The sensitivity to noise is shown in Figure 3. The results show that at a noise levels below a rms of one degree the cross-correlation function is able to determine the exact phase shift 100% of the time. By a noise level of two, the accuracy of determining exact phase shift reduces to approximately 75%. By a noise level of ten, the accuracy reduces to about 20%.

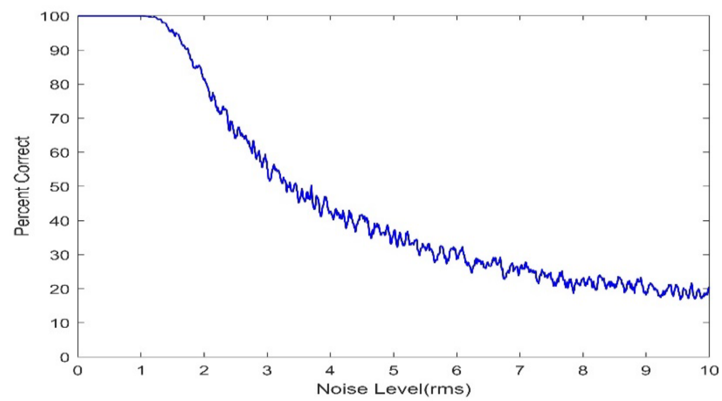


Figure 3: Percent of time shifts accurately determined using the cross-correlation function at different levels of Gaussian random noise. Data was smoothed using in a moving average of 5 points.

DISCUSSION

The results show that if the noise levels can be kept below one degree rms, they have no impact on the ability of the cross-correlation function to synchronize the data sets. However, at higher levels of noise or measurement error, the ability to exactly determine the phase shift reduces. One notable point is that even though the cross-correlation function was able to only determine accurately the phase shift only 20% of the time at the maximum noise level, the magnitude of the error was typically only 1-2% of the gait cycle (see Figure 2). This implies that even if the neural prosthesis is not able to exactly time the stimulation, it may still be close.

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