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Comparison of Chaotic Parameters between Men and Women in a Treadmill Walking*

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Abstract
A gait analysis was performed to estimate chaotic behavior of the human body motion. The purpose of this study is to apply the chaos analysis technique to joint motions of both upper and lower extremities and to compare their characteristics between men and women. A novel approach is to extend the nonlinear chaos analysis to eleven major joints including the neck and both the upper and the lower extremities. The maximal Lyapunov exponent (MLE) was calculated from the time series of the flexion-extension angle of each joint. Differences in MLE values showed no statistical significance between the right and the left sides, nor between men and women for every joint. For overall joints, however, the MLE values were found to be statistically different between the two genders ($p<0.05$). The correlation analysis between two different joints also showed statistical difference between the two genders. These results will address differences in the chaotic characteristics of the joint movements between men and women during the treadmill walking.

Key words: Gait Analysis, Chaos Analysis, Maximal Lyapunov Exponent, Upper and Lower Extremity Joints

1. Introduction

Walking is highly coordinative and combined movements of the upper and lower extremity joints to move forward with a desired speed. It has been reported that every person shows different walking patterns depending on the cultural traits as well as psychological and physical conditions such as personalities and physique [(1)]. Even for the same person, the upper and lower extremity joint motions are observed to be different between one gait cycle and another during normal walking, while they experience continuous and repetitive motions as one limb typically provides support in stance phase while the other limb moves forward in swing phase [(2)]. Furthermore, the involvement of musculoskeletal and nervous systems in the upper and the lower extremities makes their motions much more complicated leading to difficulties in determining reference parameters and analytical methods. Despite these difficulties, many studies have been reported to identify walking patterns and joint motions under various walking conditions, mainly focusing on the comparison of healthy subjects with patients of joint dysfunctions [(3)-(4)] and the comparison of young subjects with old subjects [(5)-(8)].

Recently, a quantification of the chaotic joint motions has been performed to evaluate their dynamic characteristics by calculating diverse parameters such as stride-to-stride variations [(9)-(11)], entropy [(12)-(14)], and Lyapunov exponent [(16)-(20)]. However, dynamic charac-

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teristics of upper and lower joint motions have not been quantified and compared well between normal healthy male and female groups in a treadmill walking.

A quantification of joint motions would be very helpful to understand how the total body establishes its dynamic stability and provide insights into the rehabilitation of patients with joint diseases and surgeries. In the recent studies, a nonlinear analysis with chaos theory has been employed to interpret human joint motions during walking, reporting that human joint motions possess nonlinear chaotic characteristics of a typical deterministic dynamic system. Stergiou et al. assessed dynamic stability of the knee joints with ACL (anterior cruciate ligament) injuries by calculating Lyapunov exponent [(17)], while Buzzi et al. investigated the effect of age on dynamic stability of the knee [(18)]. Ford et al. [(21)] showed that an arm constraint led to the alteration of walking frequencies and phase relations between the arm and leg, and based on this result, they concluded a high correlation between upper and lower extremity joints. However, the majority of the studies on the joint motions have focused on the lower extremities.

Therefore, the first objective of this study was to determine chaotic characteristics of both upper and lower extremity joints in a physiological walking environment. For a total of twenty young healthy subjects (10 males and 10 females), the MLE (maximal Lyapunov exponent) values were calculated based on a nonlinear analysis with chaos theory. The second objective was to investigate differences in chaotic characteristics of the flexion-extension angles between the male and the female groups as well as between the right and the left joints.

2. Materials and Methods

2.1 Motion measurement

Twenty young and healthy subjects (ten men: 24.0±4.1 years, 175.3±8.0 cm, 73.7±11.7 kg, walking speed, 1.01±0.14 m/s; ten women: 23.4±3.8 years, 159.1±4.8 cm, 52.3±5.4 kg, walking speed, 0.86±0.10 m/s) were volunteered for gait analysis. Joint movements of each subject were recorded for 90 seconds on a treadmill (KEYTEC® AC9, Taiwan) using a three-dimensional motion capture system with eight video cameras (DCR-VX2100, Sony, Japan). Prior to the measurement of joint motions, all subjects were given enough time to perform walking exercise on the treadmill with the same walking pattern as in daily life.

Thirty one reflective markers (Fig. 1) were attached on the selected bony landmarks of the subjects to calculate the flexion-extension angles of the upper and the lower extremities. All the attachment tasks were performed by one investigator to minimize the possible positioning error.

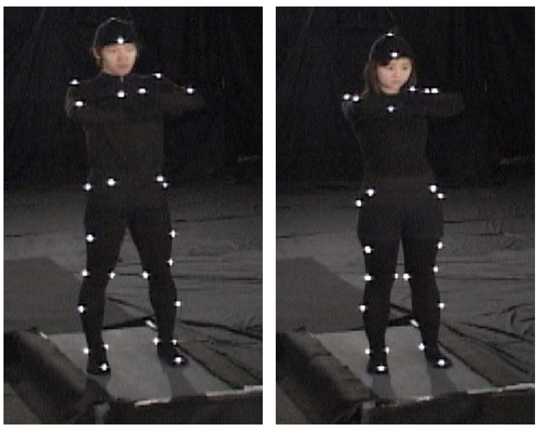


Fig. 1 Hemispherical reflective markers attached on bony landmarks

The flexion-extension angle of each joint was calculated from the inner product of the two vectors representing the longitudinal axes of the adjacent body segments at that joint (Fig. 2). The primary markers (attached markers) and the secondary markers (virtual markers) were used to define the flexion-extension angles of the neck (θ_1), shoulder (θ_2), elbow (θ_3), hip (θ_4), knee (θ_5), and ankle (θ_6) as in the figure. For example, the knee joint center, where one of the secondary markers was assumed to locate, could be determined by averaging the coordinates of two primary markers attached on the lateral and medial epicondyles. Motion data were collected at 60 frames per second and then analyzed through KWON3D motion analysis software (Visol Corp., Korea).

2.2 Time series analysis

As one of chaotic parameters of the joint motions, the MLE was selected and calculated through the times series analysis technique. The MLE is a measure of reflecting sensitivity to the initial condition, which means that a prediction of the joint motion becomes more difficult for a larger MLE value. The MLE can be calculated by considering distances between the two neighboring trajectories in a reconstructed n-dimensional state space from time series data. A set of these trajectories for a joint in the state space are called an attractor which has nonlinear dynamic information on the joint.

Figure 3 shows the procedure of the calculation of the MLE. An n-dimensional attractor was reconstructed by vector: $y(t)=[x(t), x(t+T), x(t+2T),..., x(t+(d_e-1)T)]$, where $x(t)$ was the time series of the flexion-extension angle, T was the time delay, and d_e was the embedding dimension. Time delay T was calculated by using AMI (average mutual information) function [22] so that $x(t)$ and $x(t+T)$ might have the least. Embedding dimension n was determined from GFNN (global false nearest neighbor) algorithm [23]. The GFNN algorithm states that the nearest neighbors turn out to be false when the number of the state space dimension is less than a desired value, and all these false nearest neighbors disappear in the proper embedding dimension. Based on the reconstructed attractor, Wolf algorithm [24] was employed to compute the MLE. The principle of this algorithm is to calculate the diverging ratio between the two neighboring trajectories in the state space. It is known that

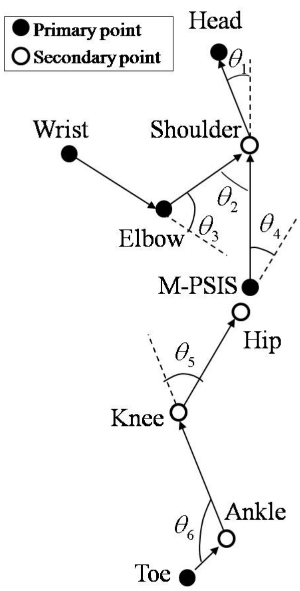


Fig. 2 Human link model constructed with the primary and secondary markers

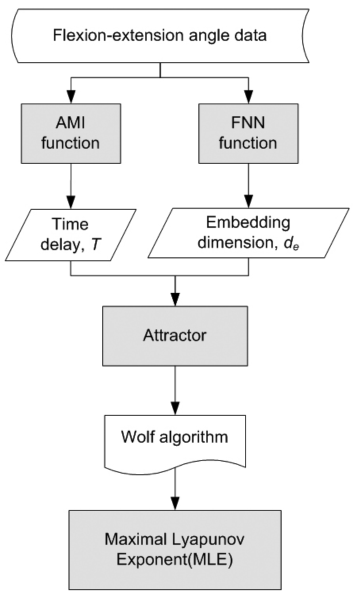


Fig. 3 Flowchart of MLE calculation from the measured joint angle

the joint motions are periodic when their MLE values are zero, while their chaotic behavior increases with an increase in MLE values. MLE values for the eleven joints were computed by Chaos Data Analyzer (Physics Academy Software, Raleigh, USA). More detailed descriptions of this procedure can be taken from the study of PARK et al. [15].

The statistical analysis was performed based on the study of Grassberger at al. [25]: the local Lyapunov exponents can be treated as independent random fluctuations, thus validity of the central theorem leads to a normal distribution for the MLE. Even for a relatively small sample size of this study, tests of normality (Shapiro-Wilk) revealed that the MLEs for all joints except the elbow were in normal distribution.

The one-way and two-way ANOVA tests were performed using SPSS (SPSS Inc., USA) in order to investigate any statistical difference in the mean values of MLEs for the eleven joints. The independent variable was gender in one-way ANOVA test; gender and joint in two-way. In all cases the significance level was set at 0.05. The correlation analysis was also performed to examine relationships between the two different joints of any pair.

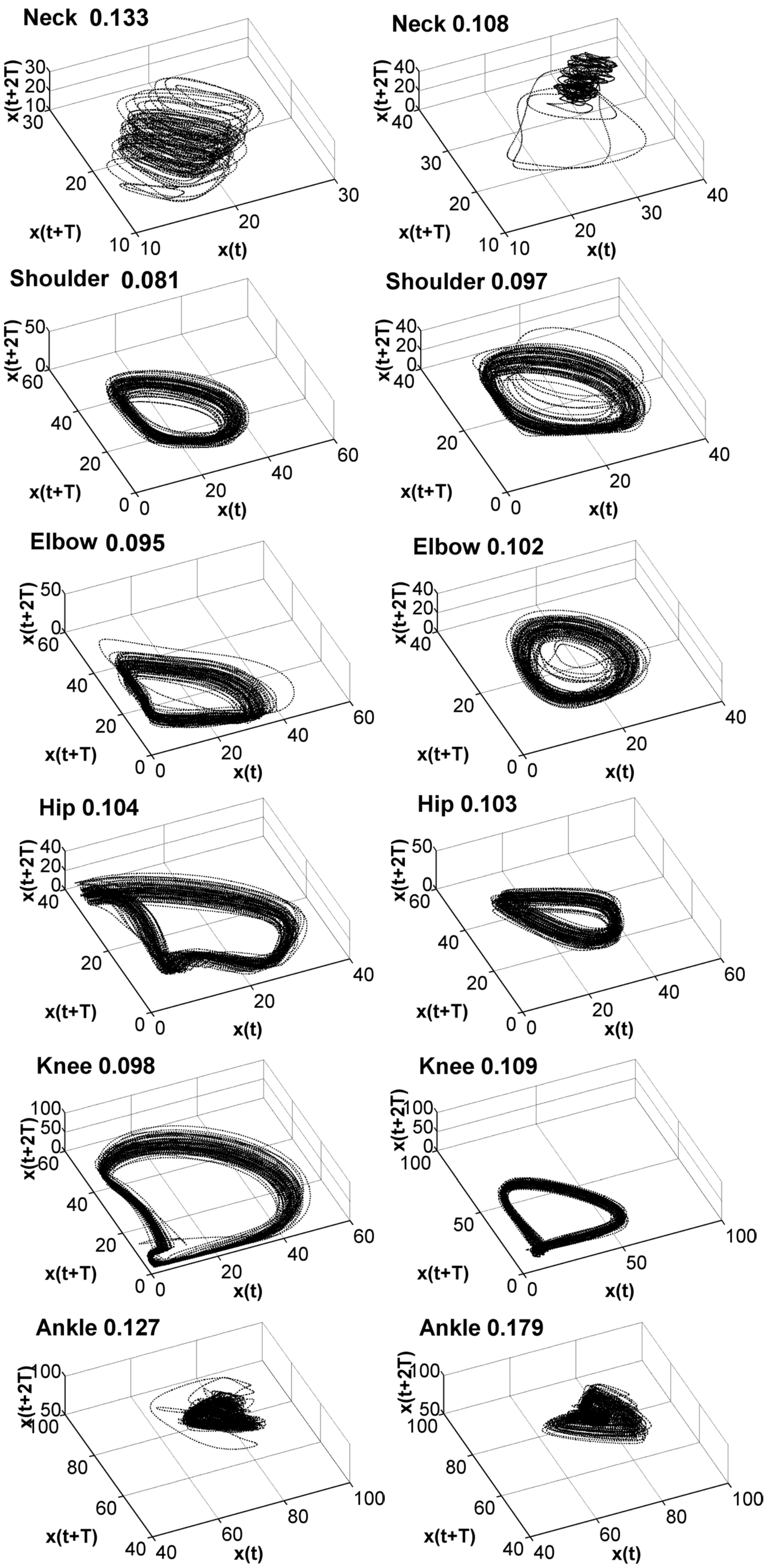
3. Result and Discussion

With the reconstructed state vector from the time series of each joint, the corresponding attractor can be plotted in a three-dimensional space. Attractor shapes for six joints are illustrated for a typical male and female as in Fig. 4, and their shapes look slightly different between men and women even for the same joints (e.g., knees or hips). These differences in attractor shapes between joints result in joint-dependent MLE values, and MLE indicates sensitive dependence on initial conditions. Negative and positive MLE values exhibit local joint stability and instability, respectively. When the periodicity in the attractor shape becomes increased, the positive MLE reduces to a lower value.

Table 1 lists the mean values and standard deviations of MLEs for all eleven joints. MLE mean values of the eleven joints ranged from 0.082 (left shoulder) to 0.180 (left ankle) for the males, and from 0.090 (right shoulder) to 0.184 (left ankle) for the females. These joint-dependent MLE values suggest the different roles of the upper and the lower extremities in securing the stability of the body in the treadmill walking. Moreover, these understandings unveil how the human body establishes its local dynamic stability and provide helpful insights into developing the clinical rehabilitation strategies of patients with joint diseases. The flexion-extension angles of the ankle joints produced the highest values of MLE among the eleven joints for both men (0.157-0.180) and women (0.160-0.184). It is also consistent with the complicated and irregular shapes of the ankle joint attractors, and can be explained by the role of ankle joints in walking. For example, the ankle joint motion can be more unstable than the motions of the hip and the knee joints due to much more irregular movements of the ankle in the process of securing the stability of the foot when the foot contacts the ground during the treadmill walking.

No statistically significant differences in MLE were observed between the right and the left sides, nor between the men and the women for the same joints ($p>0.05$). However, it was found that significant statistical differences existed between the males and the females for all joints (i.e., statistical analysis between the two genders was performed for overall joints including different joints without limiting to the same joints), and that it was also consistent with the slightly lower MLE mean values of the males (0.116) than those of the females (0.122) as in Fig. 5. This result suggests that joint motions of the upper and lower extremities of men are more stable and periodic than those of women.

The correlation analysis was performed to investigate the relationships between the two different joints of any possible pair. As shown in Table 2, statistically significant correlation between the two different joints was demonstrated by a solid circle or square for the males,



(a) man (b) woman

Fig. 4 Typical three-dimensional attractors and the corresponding MLE values of six joints for a man (a) and a woman (b)

Table 1 Maximal Lyapunov exponents of eleven joints (Mean±SD)

Joint		Left	Right
Neck	Men	0.132±0.036	
	Women	0.120±0.041	
Shoulder	Men	0.082±0.018	0.083±0.012
	Women	0.093±0.011	0.090±0.016
Elbow	Men	0.110±0.020	0.114±0.015
	Women	0.137±0.047	0.122±0.027
Hip	Men	0.099±0.020	0.095±0.012
	Women	0.102±0.014	0.102±0.013
Knee	Men	0.102±0.016	0.115±0.017
	Women	0.112±0.015	0.117±0.016
Ankle	Men	0.180±0.045	0.157±0.039
	Women	0.184±0.045	0.160±0.048

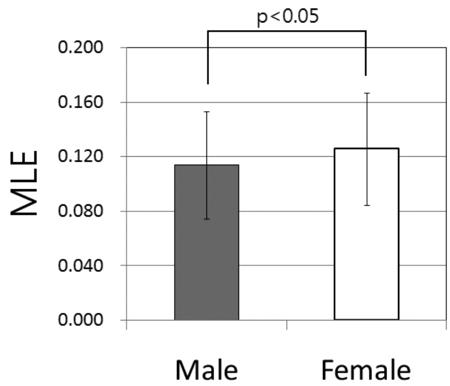


Fig. 5 Statistical difference in MLE values between the two genders for overall joints

Table 2 Correlated joint pairs with significance levels of p=0.05(●) and 0.01(■) for the males, and p=0.05(○) and 0.01(□) for the females

Joint	Neck	Sh.(L)	Sh.(R)	Eb.(L)	Eb.(R)	Hp.(L)	Hp.(R)	Kn.(L)	Kn.(R)	Ak.(L)	Ak.(R)
Neck						○				□	
Sh.(L)			●			■					○
Sh.(R)						■					
Eb.(L)					■	□	○				
Eb.(R)							■				
Hp.(L)							○				
Hp.(R)								□			
Kn.(L)									○		
Kn.(R)										■	
Ak.(L)											
Ak.(R)											

*Abbreviations: Sh.(shoulder), Eb.(elbow), Hp.(hip), Kn.(knee) and Ak.(ankle)

and by an open circle or square for the females depending on the significance level. The number of correlated joint pairs of the males and the females were six and eight, respectively, which suggests that the joint movements of the females are more combined and coordinative than those of the males in the treadmill walking. The hip joints were most highly correlated with other joints for both men and women. For the males, the left hip was correlated with the left and the right shoulders, and the right hip with the right elbow. For the females, the left hip was correlated with both the neck and the left elbow, and the right hip with both the left elbow and the left hip. This result suggests that the hip plays an important role in establishing dynamic stability of the human body motion due to its high correlation with other joint motions during the normal gait. The correlated pairs between the right and the left sides of the five joints except the neck, which has neither right nor left side, were the shoulder and the elbow for the males and the knee for the females. This small number of correlated joints between the right and the left sides was unexpected because the joint motions between the right and the left sides are generally assumed to be alternating and complementary each other in the treadmill walking. In the present study, an interesting result of the correlation analysis between two different joints was that no single correlated joint pair was overlapped between the males and the females.

Regarding the correlation between one joint in the upper extremity and another in the lower extremity, the numbers of the correlated joint pair were three and five for the males and the females, respectively. This result implies that men utilize the upper extremity joints more dynamically than women in normal walking where all of the upper and lower extremity joints observed in this study are involved in maintaining the walking stability of the human body.

4. Conclusion

This study reported joint-dependent differences in dynamic characteristics of eleven upper and lower extremity joints from ten male and ten female subjects using chaos analysis technique. The main finding of this study was that both MLE values of the eleven joints and their correlations were statistically different between the males and the females during the treadmill walking. These differences suggest that walking patterns utilizing these extremity joints can also be different between men and women. To the best of our knowledge, these results represent the first such comparisons of joint motions of all extremity joints between the genders. These findings provide greater insights into the gait analysis and its influence on differences in upper and lower extremity joint motions of normal healthy subjects, and can be employed to develop the clinical exercise modalities of patients with joint dysfunctions. Moreover, the results obtained in this study can serve as criteria for local joint stability of normal healthy subjects during the treadmill walking. In future studies, the data from patients with abnormal joints can be used for further comparison between the normal and the abnormal. Investigation of dynamic characteristics from diverse age groups would also be valuable for diagnostic purposes.

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