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Contribution of arm swing to dynamic stability based on the nonlinear time series analysis method*

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***Abstract*—It is human nature to swing their arms at the frequency of leg motion during walking, but the contribution of arm swing to dynamic stability of human motion segments was poorly understood. Based on the nonlinear time series analysis method, the objective of this study was to investigate the effects of arm swing in three conditions (natural, active and restricted arm swing) on the dynamic stability of spine and lower extremity joints, and to further assess the contribution of arm swing to the human dynamic stability in relation with age.**

Gait experiments were carried out for 10 young and 8 middle-aged healthy volunteers while walking with natural, active and restricted arm swing. The maximum finite time lyapunov exponents were calculated to quantify the local dynamic stability of spine and lower extremity joints under three arm swing conditions, and the percentage change of the maximum Lyapunov exponents was compared between two groups to evaluate the effectiveness of active arm swing in relation with age.

For both young and middle-aged groups, no significant difference of the maximum lyapunov exponents of all motion segments was found between walking with natural arm swing and with restricted arm swing (*P*>0.05). However, the maximum lyapunov exponents of all motion segments while walking with active arm swing was significantly lower than those while walking with natural arm swing and restricted arm swing, respectively (*P*<0.05), and the percentage decrease of the maximum lyapunov exponents for all motion segments while walking with active arm swing was significantly higher in middle-aged group than in young group (P<0.05). These results indicated that active arm swing would help to improve dynamic stability of human motion segments, especially more effective with age.

I. INTRODUCTION

Injury caused by falls is one of the most important factors that lead to life quality reduction, disability or death of the elderly[1]. Human balance function is an important index to reflect the fall risk. World Health Organization report shows that 70 percent of falls occur during walking[2]. Thus studies on human dynamic stability will cover the deficiency in present methods of human balance assessment, and provide a significant basis for the forecasting of falls. Dynamic stability is the ability when human bodies approach or revert to the initial balance state after disturbance during walking[3].Recently, the maximum finite time Lyapunov exponent (λ_{Max}) quantifying a system's dynamic stability, the sensitivity of the system to infinitesimal perturbations, has been applied to study the human dynamic gait stability which was controlled by neuromuscular system [4-7]. The λ_{Max} less than zero means that the gait is stable and human body can revert to the balanced state after disturbance, while chaos occur if the λ_{Max} was more than zero. The bigger the λ_{Max} is, the more unstable gait is and the more weakly human body resists disturbance.

It is human nature to swing their arms at the frequency of leg motion during walking, but the contribution of arm swing to dynamic stability of human motion segments was poorly understood. It has been showed that when arms are prevented from swinging, the energetic cost of walking increases[8, 9], but the mechanical explanation of arm swing remains unclear. Some researchers find that arm swing is an essential component of locomotion, which helps to stabilize the total moment of force acting on the vertical body axis, such as reduction of the vertical displacement of the centre of mass[8], reduction of angular momentum[10-12] and angular displacement or ground reaction moment[13]. However, few researches are carried out to study the dynamic stability of different motion segments under various arm swing conditions and the contribution of arm swing with age is unknown.

Based on the nonlinear time series analysis method, the objective of this study was to investigate the effects of arm swing in three conditions (natural, active and restricted arm swing) on dynamic stability of the spine and lower extremity joints, and to further assess the contribution of arm swing to dynamic stability with age.

II. MATERIALS AND METHODS:

A. Subjects and experimental procedures

8 middle-aged (3 women, 5 men; mean age 55.1±1.33, weight 67.05±15.30 kg, height 1.68±0.052 m) and 10 young (5 women, 5 men; mean age 23.30±0.63, weight 57.40±9.88 kg, height 1.64±0.041 m) healthy volunteers

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were selected. All test contents were told to the volunteers in advance and informed consent forms were signed.

During the experiment, subjects were instructed to walk on the treadmill at the natural speed under three arm swing conditions, that is, with natural arm swing (NAS, subjects were instructed to let their arms hang in a relaxed manner and to avoid ‘‘tensing’’ their shoulder or arm muscles), with active arm swing (AAS, subjects were instructed to swing their arms actively using their shoulder or arm muscles) and restricted arm swing (RAS, subjects were instructed to put their hands on hips and elbows projecting outwards). 39 markers were placed on the bony landmarks of body to construct a three-dimensional (3D) full body model (Fig 1), and the kinematic data during walking were collected by the three-dimensional motion capture system (VICON T40, USA).

All trials lasted five minutes with at least 5-min rest between each trial. During trials on the treadmill, subjects were required to keep head straight and avoid other actions, such as turning head, raising hands, etc. After the first two minutes, data were collected for 90 continuous seconds under both conditions.

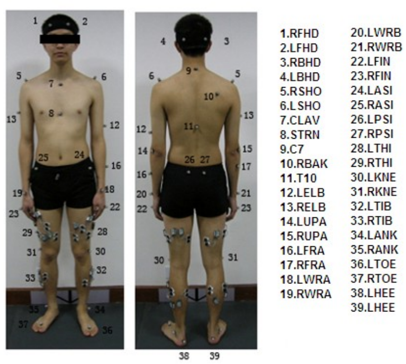

Fig.1 39 bony land markers to construct a three-dimensional (3D) full body model

B. Date analysis

The three-dimensional kinematics data were collected from five motion segments , that is, the 7th cervical vertebra (C7), the 10th lumbar vertebra (T10) and the three lower extremity joints (hip joint, knee joint and ankle joint). The first derivation of the position times series of the C7 and T10 markers were used to estimate dynamic stability of the spine. The angular acceleration of the lower extremity joints were calculated from the 3D locations of the marker set using the VICON Nexus software to estimate dynamic stability of the lower limb.

Analyses were limited to the anterior- posterior (AP), medio-lateral (ML) and vertical (VT) dimension of C7 and T10, flexion- extension (FE), abduction/adduction (AB/AD) and rotation (RT) angular acceleration of joints. 30 walking strides were selected for each subject while walking under three arm swing condition to overcome the non-stationary of time series [8].

From the time-normalized time-series and their time-delayed copies, state spaces were reconstructed using

$$X(t)=[x(t),x(t+T),x(t+2T),...,x(t+(d_E-1)T)] \quad (1),$$

where $X(t)$ is the d_E-dimensional state vector, $x(t)$ is the original data, T is the time delay and d_E is the embedding dimension. The global false nearest neighbor analysis of our own data suggested that d_E=5 was sufficient to capture most of the dynamics during human walking, which was in line with previous studies[14]. Time delays were estimated using the first minimum of the average mutual information function. We found delays ranged from 4 to 22 samples, but to assure that all the trials were analyzed similarly, a constant T=10 was used for all reconstructed state-space, since all time series had the same frequency after normalization[15].

Maximum finite-time Lyapunov exponents , λ_{Max} ,were calculated based on the algorithm published by Rosenstein et al[16]. The Euclidean distance between the nearest neighbors $d_j(t)$ was computed for each data-point j in the reconstructed state-space $Y_j(t)$ for all time *t*. The nearest neighbors were found by selecting data points from separate cycles that were closest to each other in reconstructed state-space. If repeated strides were identical in kinematics, then a plot of the trajectories would illustrate each cycle on top of the others in state-space. Under this condition, the distance between the nearest neighbors $d_j(t)$ would be zero for all pairs of nearest neighbors, j . However, in empirically measured data, the distance between the nearest neighbors, $d_j(t)$ was greater than zero. Hence, there were clearly kinematic disturbances in the data. The distance between all the nearest neighbors was tracked forward in time to record time-dependent changes in kinematic variability. The rate of change in the distance between the nearest neighbors was quantified by the maximum Lyapunov exponent λ_{Max} :

$$d_j(i)=C_j e^{\lambda(i\cdot\Delta t)}, C_j=d_j(0) \quad (2),$$

where $d_j(0)$ is the average displacement between trajectories at *t*=0. Two randomly selected initial trajectories should diverge, on average, at a rate determined by the λ_{Max} .

Therefore, the λ_{Max} was approximated from the experimental kinematic data as the slope of the linear best-fit line to the curve created by the equation (3):

$$lnd_j(i)=lnC_j+\lambda(i\cdot\Delta t) \quad (3),$$

Where $lnd_j(i) \square i$ represents the average logarithm of displacement for all pairs of nearest neighbors i .

The λ_{Max} was calculated as the slope of the logarithm of the average divergence across the span of 0–1 strides[16].

To evaluate the effectiveness of active arm swing on dynamic stability with age, the percentage decrease of maximum Lyapunov exponent, λ_d , compared with natural arm swing was calculated as: $\lambda_d = (1 - \lambda_{AAS} / \lambda_{NAS}) \times 100\%$ (4)

Where λ_{AAS} and λ_{NAS} are the maximum exponent of motion segments while walking with AAS and NAS.

C. Statistical analysis

Statistical analysis was performed to analyze the contributions of arm swing to human dynamic stability. Since the right and left limbs showed no statistically significant differences in dynamic stability in preliminary analyses, data from the right and left joints were pooled for statistical analyses. Two-factor repeated measures analysis of variance (ANOVA) was conducted to test the within-subject effects of arm swing on λ_{Max} using SPSS software (version 17.0,SPSS Inc., USA) with a significance level of $P<0.05$.

III. RESULTS

A. Effect of arm swing on local dynamic stability

For both young and middle-aged groups, the λ_{Max} of all motion segments in the various motion directions while walking with AAS was lower than that while walking with NAS and with RAS, respectively (P<0.05). There was no significant difference in λ_{Max} of all motion segments between NAS and RAS, *P*>0.05 (Tab 2 and 3). Overall, compared with walking with NAS and RAS, the λ_{Max} was significantly decreased while walking with AAS.

Tab.2.the λ_{Max} of the middle-aged group

Segment	direction	NAS	RAS	AAS	P	P^{*}	P^{**}
C7	AP	2.86±0.33	2.87±0.35	2.51±0.28	>0.05	<0.05	<0.05
	ML	2.79±0.38	2.75±0.40	2.21±0.21	>0.05	<0.05	<0.05
	VT	2.38±0.27	2.37±0.23	2.03±0.15	>0.05	<0.05	<0.05
T10	AP	2.96±0.29	2.98±0.26	2.56±0.21	>0.05	<0.05	<0.05
	ML	2.67±0.34	2.74±0.39	2.10±0.18	>0.05	<0.05	<0.05
	VT	2.42±0.22	2.45±0.22	2.05±0.18	>0.05	<0.05	<0.05
Hip	FE	2.73±0.24	2.77±0.36	2.52±0.21	>0.05	<0.05	<0.05
	AB/AD	2.49±0.32	2.63±0.36	2.20±0.14	>0.05	<0.05	<0.05
	RT	1.99±0.33	1.99±0.46	1.86±0.30	>0.05	<0.05	<0.05
Knee	FE	2.69±0.39	2.63±0.41	2.50±0.32	>0.05	<0.05	<0.05
	AB/AD	2.19±0.41	2.38 ±0.47	2.00±0.28	>0.05	<0.05	<0.05
	RT	2.03+0.33	2.09±0.39	1.97±0.27	>0.05	<0.05	<0.05
Ankle	FE	2.15±0.29	2.25±0.37	1.96±0.10	>0.05	<0.05	<0.05
	AB/AD	2.06±0.25	2.08±0.41	1.88±0.16	>0.05	<0.05	<0.05
	RT	2.05+0.24	2.08±0.40	1.87±0.16	>0.05	<0.05	<0.05

AP: anterior- posterior, ML: medio-lateral, VT: vertical, FE: flexion-extension, AB/AD: abduction/adduction, RT:rotation; NAS: with natural arm swing, RAS: with restricted arm swing, AAS: with active arm swing; *P*: for NAS vs. RAS, P^{*}: for AAS vs NAS, P^{**}: for AAS vs RAS

Tab.3.the λ_{Max} of the young group

Segment	direction	NAS	RAS	AAS	P	P^{*}	P^{**}
C7	AP	2.44±0.27	2.42±0.29	2.36±0.35	>0.05	<0.05	<0.05
	ML	2.29±0.18	2.25±0.29	2.05±0.41	>0.05	<0.05	<0.05
	VT	1.94+0.29	1.95±0.26	1.82±0.36	>0.05	<0.05	<0.05
T10	AP	2.37±0.29	2.41±0.31	2.20±0.32	>0.05	<0.05	<0.05
	ML	2.05±0.21	2.16±0.29	1.96±0.37	>0.05	<0.05	<0.05
	VT	1.84±0.25	1.91±0.22	1.74±0.34	>0.05	<0.05	<0.05
Hip	FE	2.36±0.14	2.29±0.24	2.16±0.30	>0.05	<0.05	<0.05
	AB/AD	2.04±0.17	2.13±0.23	1.82±0.31	>0.05	<0.05	<0.05
	RT	1.61±0.23	1.77±0.15	1.46±0.29	>0.05	<0.05	<0.05
Knee	FE	2.21±0.23	2.23±0.27	2.02±0.29	>0.05	<0.05	<0.05
	AB/AD	1.73±0.34	1.87±0.22	1.62±0.26	>0.05	<0.05	<0.05
	RT	1.67+0.22	1.78±0.13	1.60±0.21	>0.05	<0.05	<0.05
Ankle	FE	1.88±0.19	1.87±0.26	1.63±0.28	>0.05	<0.05	<0.05
	AB/AD	1.85±0.23	1.90±0.18	1.52±0.29	>0.05	<0.05	<0.05
	RT	1.86+0.23	1.90±0.18	1.73±0.30	>0.05	<0.05	<0.05

AP: anterior- posterior, ML: medio-lateral, VT: vertical, FE: flexion-extension, AB/AD: abduction/adduction, RT:rotation; NAS: with natural arm swing, RAS: with restricted arm swing ,AAS: with active arm swing; *P*: for NAS vs.RAS, P^{*}: for AAS vs NAS, P^{**}: for AAS vs RAS

B. Effect of active arm swing on dynamic stability with age

For all motion segments in the various motion directions, the λ_d in middle-aged group was significantly decreased than that of young group while walking with AAS (*P*<0.05). For the spinal C7 and T10 motion segments, the maximum decrease of λ_d in the middle-aged group while walking with active arm was found in the mediolateral motion directions (decrease of 20.37% and 20.27%, respectively), and the a larger decrease percentage was found in middle-aged group than in young group(decreased of 15.20% and 12.73% respectively) (*P*<0.05).

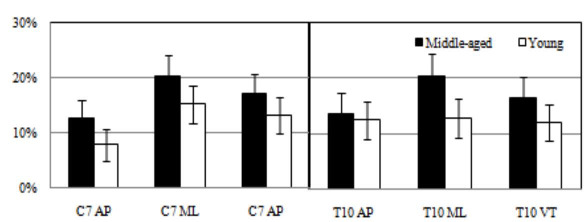

Fig.3.The λ_d of the C7 and T10 between the two groups

For the lower extremity joints, the maximum decrease of λ_d in the middle-aged group while walking with active arm was found in the hip joint rotation (decrease of 19.38%), knee joint abduction/adduction (decrease of 17.64%) and ankle joint abduction/adduction (decrease of 16.47%), and a larger decrease percentage was found in middle-aged group than in young group (decrease of 18.23%, 12.75% and 16.05% respectively)(P<0.05).

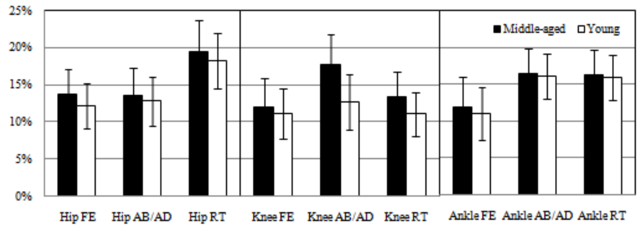

Fig.4. The λ_d of the lower extremity between middle-aged group and young group

IV. Discussion and Conclusion

The aim of the study was to investigate the effects of arm swing in three conditions (natural, active and restricted arm swing) on the dynamic stability of spine and lower extremity joints, and to further assess the contribution of arm swing to the human dynamic stability in relation with age. We found that there was no significant difference in local dynamic stability of the motion segments between subjects walking with natural arm swing and with restricted arm swing ($p>0.05$), which was consistent with the previous reports that the effect of natural arm swing is on recovery from a perturbation which may contribute to the overall stability of human gait rather than on local dynamic stability [10,17,18].

However, compared with walking with natural arm swing and restricted arm swing, we found that the local dynamic stability of all motion segments was significantly increased while walking with active arm swing ($p<0.05$). Furthermore, by analyzing the percentage decrease of the maximum Lyapunov exponent while walking with active arm swing, we also found that the active arm swing improve more local dynamic stability of all motion segments in various motion directions in middle-aged group than in young group. Since human balance function will be decreased with age, our findings strongly suggest that the decreased human dynamic stability with age should be compensated by the active arm swing during walking, which may be more effective for the elderly who are easy to fall.

The limitation of the present study was that the effect of active arm swing with age was compared between young and middle-aged groups. Though the significant result was achieved in the current study, the further work will be done for young and elderly subject to demonstrate the positive effect of active arm swing on the human gait stability.

In conclusion, the active arm swing would help to improve the local dynamic stability of human motion segments, especially more effective with increased age.

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