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Age-independent and age-dependent sex differences in gait pattern determined by principal component analysis

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ABSTRACT

Although various studies have reported significant sex differences in pelvic and/or hip-joint motion during normal walking in healthy adults, it is still unclear whether such differences are among the most dominant age-independent sex differences. This study was conducted to analyze the whole waveform of lower-extremity joint kinematics obtained from 191 healthy adults using a principal component analysis (PCA). The PCA was conducted using a 955×1212 input matrix constructed from the participants' time-normalized pelvic and right-lower-limb-joint angles along three axes (five trials of 191 participants $\times$ 101 data points $\times$ 4 angles $\times$ 3 axes). Two-way (age $\times$ sex) analyses of variance were conducted on the principal component scores (PCSs) of principal component vectors (PCVs) 1 through 6, each of which explained more than 5% of the variance. We identified a PCV that exhibits a significant age–sex interaction (PCV 1). The characteristics of sex differences reported in previous studies could be observed in the reconstructed waveforms of this PCV. Thus, we can conclude that the sex differences in the gaits reported in previous studies are not consistent across age groups. Furthermore, we also found a PCV that exhibited only a significant sex difference (PCV 6). This PCV was the first and only PCV to exhibit a sex difference without any age-related effect or age–sex interaction. Therefore, we concluded that the movement related to this PCV is age-independent and is the most dominant sex difference in the gaits observed during normal walking.

1. Introduction

Walking is the most essential means of human locomotion. Therefore, the understanding of gaits is applicable not only to clinical purposes (e.g., the design of gait-specific training, rehabilitation, or treatment) but also to business purposes (e.g., the design of gait-specific footwear/garments, sensor-based applications, or surveillance and tracking services).

Multiple studies have reported significant sex differences in gaits, mainly in pelvic and/or hip-joint motions, during normal walking in healthy adults (for pelvic motion [1–3]; for hip motion [2–4]). Bruening et al. [3] suggest that these findings can be used to design sex-dependent services or products. However, these studies only investigated the sex differences in a relatively small age range. Therefore, it is still unclear whether the sex differences in the gaits reported in previous studies are consistent across all age groups. The data presented by Youdas et al. [12] indicate the existence of an interaction between age and sex in the pelvic posture while a person is standing normally, i.e., females tend to exhibit greater pelvic sagittal angles than males, while the sagittal angle of the pelvis tends to decrease with age, especially in the case of females. This implies that there is an interaction between sex and age regarding the pelvic sagittal angle, even during walking.

Furthermore, these studies only investigated selected variables at discrete time points. Nigg et al. [5] recently noted that the success of this approach depends on the selection of the variables made by the investigators and can fail to detect potentially interesting results in the large portions of the data left unanalyzed. Therefore, it is still unclear whether previous studies have revealed the most dominant sex differences in gaits. Recently, principal component analysis (PCA) has attracted increasing interest in biomechanical studies because of its usefulness in identifying the movement characteristics of various groups under various conditions using whole data waveforms [5–11]. PCA is a multivariate statistical technique that summarizes the information

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conveyed by a large number of correlated variables using a smaller number of uncorrelated variables (principal components). PCA generates principal component vectors (PCVs) and a set of principal component scores (PCSs) for each PCV. Each PCV corresponds to an axis of variance, and a PCS is a projection of the input data onto each PCV. Movements with dominant differences (large variances) arise in lower-numbered PCVs and vice versa. Moreover, the waveforms related to each PCV can be reconstructed by adding and subtracting the PCSs. We therefore concluded that PCA could be useful in clarifying whether the previous studies cited focused on the most dominant sex differences in gaits.

The objective of this study was to use PCA to clarify the age-independent and most dominant sex differences observed in gaits during normal walking. We hypothesized that the differences in pelvic and/or hip-joint motions reported in a previous study are among the most dominant sex differences but that they vary with age.

2. Methods

2.1. Participants

Walking gait data were obtained from 191 healthy adults (99 males and 92 females) aged 20 to 75. The demographics of the participants are presented in Table 1. All of the participants were able to walk independently without assistive devices (e.g., canes, crutches, or orthotic devices), had normal or corrected-to-normal vision, had no history of neuromuscular disease, and lived independently in the local community. Those who had trauma

Table 1
Subject demographic data. Significance was judged to be significant when η^2 value > 0.06.

Variables	All mean ± SD	Males mean ± SD	Females mean ± SD	Age effect	Sex effect	Interaction
	All $N=191$	All $N=99$	All $N=92$	p-Value	p-Value	p-Value
		Young $N=31$	Young $N=36$	η^2	η^2	η^2
		Middle $N=22$	Middle $N=21$			
		Elderly $N=46$	Elderly $N=35$			
Age [years]				$p<0.01$	$p<0.01$	$p<0.01$
All	50.26 ± 18.66	51.15 ± 18.73	49.30 ± 18.54	$\eta^2=0.927$	$\eta^2=0.028$	$\eta^2=0.017$
Young	27.21 ± 5.37	26.19 ± 5.37	28.08 ± 5.22			
Middle	52.74 ± 7.55	51.09 ± 7.03	54.48 ± 7.72			
Elderly	68.01 ± 2.82	68.00 ± 2.71	68.03 ± 2.97			
Height [cm]				$p<0.01$	$p<0.01$	n.s.
All	163.00 ± 8.55	168.32 ± 6.58	157.27 ± 6.46	$\eta^2=0.259$	$\eta^2=0.504$	
Young	165.48 ± 8.17	171.94 ± 5.28	159.92 ± 5.77			
Middle	165.37 ± 8.43	171.27 ± 5.65	159.19 ± 6.1			
Elderly	159.69 ± 7.78	164.48 ± 5.61	153.40 ± 5.39			
Body mass [kg]				$p<0.01$	$p<0.01$	$p<0.01$
All	60.12 ± 12.05	67.12 ± 11.27	52.59 ± 7.45	$\eta^2=0.023$	$\eta^2=0.384$	$\eta^2=0.057$
Young	61.04 ± 15.23	72.03 ± 15.22	51.58 ± 6.25			
Middle	60.28 ± 11.05	67.55 ± 8.07	52.67 ± 8.29			
Elderly	59.27 ± 9.22	63.61 ± 7.65	53.57 ± 7.94			
Velocity [m/s]				$p<0.01$	n.s.	$p<0.01$
All	1.35 ± 0.16	1.34 ± 0.18	1.37 ± 0.14	$\eta^2=0.042$		$\eta^2=0.017$
Young	1.36 ± 0.15	1.37 ± 0.17	1.36 ± 0.13			
Middle	1.41 ± 0.19	1.41 ± 0.23	1.40 ± 0.14			
Elderly	1.32 ± 0.15	1.29 ± 0.14	1.36 ± 0.15			
Step length [cm]				$p<0.01$	$p<0.01$	n.s.
All	69.88 ± 6.90	71.23 ± 7.32	68.42 ± 6.10	$\eta^2=0.074$	$\eta^2=0.059$	
Young	71.82 ± 5.88	73.09 ± 6.15	70.72 ± 5.42			
Middle	70.46 ± 8.28	72.85 ± 9.46	67.96 ± 5.92			
Elderly	67.96 ± 6.36	69.20 ± 6.31	66.33 ± 6.07			
Step width [cm]				$p<0.01$	$p<0.01$	$p<0.01$
All	9.11 ± 2.81	9.63 ± 2.92	8.54 ± 2.57	$\eta^2=0.015$	$\eta^2=0.029$	$\eta^2=0.010$
Young	8.58 ± 2.83	8.81 ± 3.25	8.38 ± 2.40			
Middle	9.32 ± 2.25	9.73 ± 2.41	8.89 ± 1.99			
Elderly	9.43 ± 3.00	10.14 ± 2.79	8.49 ± 3.01			
Stance time [s]				$p<0.01$	$p<0.01$	$p<0.01$
All	0.59 ± 0.05	0.61 ± 0.05	0.57 ± 0.05	$\eta^2=0.072$	$\eta^2=0.168$	$\eta^2=0.030$
Young	0.60 ± 0.05	0.61 ± 0.05	0.59 ± 0.04			
Middle	0.57 ± 0.05	0.59 ± 0.05	0.55 ± 0.03			
Elderly	0.58 ± 0.05	0.61 ± 0.04	0.55 ± 0.04			
Swing time [s]				$p<0.01$	$p<0.01$	$p<0.01$
All	0.41 ± 0.03	0.42 ± 0.03	0.40 ± 0.03	$\eta^2=0.052$	$\eta^2=0.056$	$\eta^2=0.030$
Young	0.42 ± 0.03	0.42 ± 0.03	0.41 ± 0.03			
Middle	0.40 ± 0.04	0.40 ± 0.05	0.39 ± 0.02			
Elderly	0.41 ± 0.03	0.42 ± 0.03	0.39 ± 0.03			
Step frequency [Hz]				$p<0.01$	$p<0.01$	$p<0.01$
All	1.01 ± 0.08	0.98 ± 0.07	1.04 ± 0.07	$\eta^2=0.076$	$\eta^2=0.136$	$\eta^2=0.039$
Young	0.99 ± 0.07	0.97 ± 0.07	1.00 ± 0.07			
Middle	1.04 ± 0.08	1.01 ± 0.09	1.07 ± 0.05			
Elderly	1.01 ± 0.08	0.97 ± 0.07	1.06 ± 0.08			