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ORIGINAL ARTICLE

Effect of speed on the upper and contralateral lower limb coordination during gait in individuals with stroke

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Abstract The purposes of this study were to investigate the upper and contralateral lower limb coordination and to study the effect of speed on the upper and contralateral lower limb coordination in individuals with stroke and control groups. Thirty individuals with stroke who were able to walk independently without using any assistive devices and 30 control individuals were recruited for the study. Upper and contralateral lower limb coordination was analyzed using the shoulder and contralateral hip displacements in the sagittal plane. All data were analyzed by three-dimensional gait analysis. Results demonstrated high degrees of coordination in the upper and contralateral lower limbs of the controls and in the unaffected upper and affected lower limbs of individuals with stroke. Gait speed was found to be associated with the upper and contralateral lower limb coordination in individuals with stroke but not in the controls. The findings implied that the affected upper limb plays an important role for improving gait coordination and is necessary for gait performance in individuals with stroke. Thus, health professionals should exercise the affected arm to increase efficiency of walking in individuals with stroke.

Introduction

A high degree of temporospatial coordination is demonstrated in inter- and intralimb segments for bipedal human gait. Evidence supported that interlimb coordination is mediated by spinal interneuronal circuits which are under the supraspinal control [1]. This neuronal control regulates the upper and lower limb circuits manifested in the arm swing during walking as a residual function of quadrupedal

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locomotion [2]. Lower limb coupling relates to a state of lower limb coordination, temporospatials, as well as specific neural signals from the upper limbs [3–6]. The normal phase of arm swing during human locomotion plays an active role in body postural control. When amplitude of the arm and leg is increased, gait speed will be increased [7]. The cyclical motion of the upper limbs is considered a supportive component of human gait aiming for energy cost conservation [8,9]. Many researchers have demonstrated that the upper and lower limbs muscle activities are well coordinated in different locomotive tasks, such as walking [10–12], crawling [13], and swimming [14].

Coordination is considered as a higher order property of the global human body system [15]. Bruijn and coworkers [7] studied the effect of increased gait speed on thoracic and pelvic rotations. It was found that thoracic and pelvic contributions to the total body angular momentum was less than 10%, while the leg and arm contributions were approximately 90%. Although humans are able to walk without using arm swing, a greater muscle activation of the leg is required when walking with arm restriction [8,9,16]. Accurate limb coordination in gait is essential for all terrestrial animals to ensure gait safety and accomplishment. This requirement is particularly critical for humans, who have a higher center of gravity and have only two limbs for support.

Previous studies demonstrated that limb coordination during walking is deteriorated by aging and diseases [15,17–19]. However, some studies quantified locomotion coordination on nonnatural conditions. For example, the left–right phase relationship of the lower limbs was investigated during pedaling movements on a stationary bicycle or walking on a treadmill. From the discussion above, questions about upper and contralateral lower limb coordination in individuals with stroke on the natural condition remained.

Therefore, the objective of the present study was to determine the upper and contralateral lower limb coordination during walking as well as time lags of that coordination in individuals with stroke and controls. Furthermore, correlation between the upper and contralateral lower limb coordination and gait speed was investigated to determine the effect of speed on coordination in individuals with stroke and in controls.

Methods

Participants

Thirty individuals with stroke and 30 gender-matched controls participated in the present study. Each group was composed of 25 males and 5 females whose average age was 53 ± 9 years. Individuals with stroke consisted of 12 patients with hemorrhagic stroke and 18 patients with ischemic stroke who were recruited from Siriraj Hospital and Physical Therapy Clinic, Mahidol University. Inclusion criteria for this group were individuals with a first stroke and ability to walk independently without using any assistive device. Participants were excluded if they had a history of musculoskeletal diseases which interfere with walking performance, other neurological problems such as Parkinsonism or Alzheimer's disease, as well as communication and cognitive deficits as tested by Thai Mental State Examination (score <23) [20]. Healthy, age-matched individuals who had no musculoskeletal, neurological, and other problems causing abnormal gait served as controls.

This study was approved by the ethical committee, Faculty of Medicine Siriraj Hospital, Mahidol University. Informed consent was obtained from all participants before the study commenced. Characteristics of participants are shown in Table 1. The participants' motor function of lower limb was assessed using the Fugl–Meyer Assessment [21], and their lower limb muscle tone was gauged using the Modified Ashworth Scale [22] for selected muscles (hip adductors, hip extensors, knee extensors, ankle plantarflexors, and ankle invertors).

Procedures

Data collection

Before collecting the data, demographic data (gender, age, body weight, height, side of hemiparesis, time since stroke, and type of stroke), physical examinations (blood pressure, heart rate, passive range of motion, and sensation), and anthropometric measurements (knee and ankle widths and leg length) were recorded. Thirty-four spherical reflective markers were placed on bony prominence according to the Plug-In-Gait model. Six Vicon video cameras version 612

Table 1 Characteristic and clinical assessments of participants.

Characteristics	Controls	Individuals with stroke
Number of participants (*n*)	30	30
Gender (male/female) (*n*)	25/5	25/5
Age (y)	52.97 ± 8.82	53.30 ± 8.77
Body weight (kg)	64.58 ± 10.55	68.05 ± 13.96
Height (cm)	165.62 ± 6.39	166.03 ± 7.40
Hemiparesis side (left/right) (*n*)	—	22/8
Time since stroke (mo)	—	32.3 ± 19.6
Type of stroke (*n*)		
Hemorrhage	—	12
Ischemic	—	18
TMSE (score)	—	27.93 ± 1.84
FMA (score)	—	24.33 ± 5.18
MAS (score)		
Hip adductors	—	0–2
Hip extensors	—	0–2
Knee extensors	—	0–2
Ankle plantarflexors	—	0–3
Ankle invertors	—	0–3
Gait speed (m/s)		
Comfortable	1.11 ± 0.15	0.60 ± 0.22
Fast	1.55 ± 0.20	0.82 ± 0.29

FMA = Fugl–Meyer Assessment for the lower extremity; MAS = Modified Ashworth Scale; TMSE = Thai Mental State Examination.

(Oxford Metrics Ltd., Oxford, UK) were used for analyzing gait characteristics at 100 Hz of sampling rate. Two speeds of walking were tested: self-selected comfortable and fast speeds.

Data reduction and processing

Walking data were selected at the middle part of the walkway to eliminate accelerating and decelerating effects. Then, data were filtered and processed using Woltring filter routine and Polygon software. Coordination of the upper and lower limbs was computed by the cross-correlation analysis using MATLAB between shoulder and contralateral hip in the sagittal plane during one gait cycle. The median, minimum, and maximum correlation coefficients and associated time lags from this analysis were reported.

$$[\mathrm{XCF}, \mathrm{Lag}, \mathrm{Bounds}] = \mathrm{crosscorr}(\mathrm{serie\ 1},\ \mathrm{serie\ 2}),$$

where:

XCF is the cross-correlation function.

Series 1 and 2 are the observed column vectors of the first and second univariate time series.

Lags are the vector of lags corresponding to XCF (−nLags, ...,+nLags).

Bounds are the two element vectors indicating the approximate upper and lower confidence bounds.

The lowest to highest degrees of the cross-correlation coefficient ranged from 0 to 1.

For the controls, it was found that the sides (left and right) did not affect the upper and lower limb coordination. Thus, one set of upper and contralateral lower limb coordination was used as a representative data. For individuals with stroke, two set of data were presented: (1) coordination of the unaffected upper and affected lower limbs and (2) coordination of the affected upper and the unaffected lower limbs as illustrated in Fig. 1.

Statistical analysis

Normality was determined using the Kolmogorov—Smirnov goodness-of-fit test. Statistical analyses were performed with a level of statistical significance set at $p < 0.05$. It was found that shoulder and contralateral hip coordination was non-normal distribution. Thus, median and range were used for describing the data. Moreover, correlations between gait speeds and the coordination between the shoulder and the contralateral hip were assessed using the Spearman rank correlation coefficient.

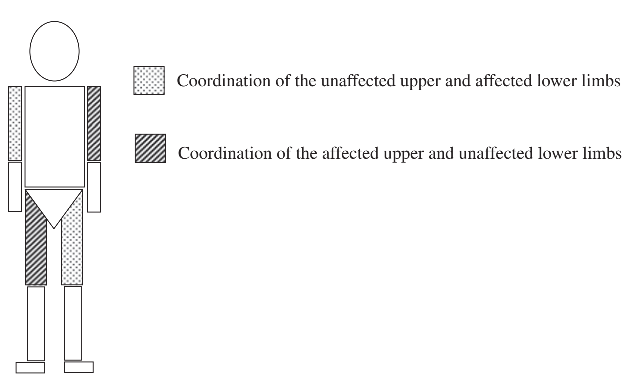

Figure 1. Coordination of the upper and contralateral lower limbs.

Results

Shoulder and contralateral hip coordination and time lags

Table 2 shows the median values and ranges of the correlation coefficient and associated time lags of the shoulder and contralateral hip in individuals with stroke and controls. In comfortable and fast gait speeds, the median correlation coefficient of the shoulder and contralateral hip, especially in the affected shoulder and unaffected hip in individuals with stroke, was less than that of the controls. Individuals with stroke showed a wide range of correlation coefficient and time lags of shoulder and contralateral hip when compared to the controls.

The median correlation coefficient of the affected shoulder and unaffected hip in individuals with stroke walking increased with fast gait speed (gait speed: comfortable 0.66, fast 0.79). In contrast, similar to the controls, the median correlation coefficient of the unaffected shoulder and the affected hip in individuals with stroke walking at comfortable gait speed was similar to that in those walking with a fast gait speed.

At both comfortable and fast gait speeds, time lags of the individuals with stroke and the controls were near zero.

Correlations between the shoulder and contralateral hip coordination and gait speed

Table 3 shows the correlations between the coordination between the shoulder and contralateral hip and gait speeds (comfortable and fast). Statistically significant correlations ($p < 0.05$) of the coordination between the shoulder and contralateral hip and gait speed were found in individuals with stroke but not in the controls. For the comfortable gait speed, moderate to high correlations were found in the coordination between the affected shoulder and the unaffected hip ($r_s = 0.488$, $p = 0.006$), and in the coordination between the unaffected shoulder and the affected hip ($r_s = 0.730$, $p = 0.001$). At fast gait speed, mild to moderate correlations are found in the coordination between the unaffected shoulder and the affected hip ($r_s = 0.394$, $p = 0.031$) and in the coordination between the affected shoulder and the unaffected hip ($r_s = 0.612$, $p = 0.001$).

Discussion

Shoulder and contralateral hip coordination and time lags

The present findings indicate that upper and contralateral lower limb coordination can definitely characterize abnormal from normal. In normal gait, the task requires complicated interlimb coordination for propelling the body forward while maintaining stability simultaneously and demonstrates movement in sequences. This task requires bilateral symmetrical control of the four limbs [15,23,24].

Table 2 Median, minimum, and maximum values of correlation coefficients and associated time lags.

Gait speeds	Individuals with stroke				Controls	
	Unaffected shoulder and affected hip		Affected shoulder and unaffected hip		Shoulder and contralateral hip	
	Correlation coefficient	Time lag (s)	Correlation coefficient	Time lag (s)	Correlation coefficient	Time lag (s)
Comfortable						
Median	0.93	0	0.66	−0.03	0.95	0
Min	0.42	−0.20	−0.71	−0.20	0.88	−0.07
Max	0.99	0.13	0.96	0.12	0.99	0
Fast						
Median	0.93	0	0.79	−0.04	0.94	0
Min	0.61	−0.15	−0.77	−0.20	0.78	−0.05
Max	0.99	0.16	0.98	0.15	0.99	0

In individuals with stroke, movement incoordination may come from disorganized postural muscle synergies and excessive muscle co-contraction [25]. In addition, more weight shifting toward the unaffected side, and compensatory movement patterns such as excessive hip and knee movements often occur during gait [26]. We found that the affected upper limb was the critical part that would be influenced during coordination of the upper and contralateral lower limb rather than the affected lower limb. In the natural condition of overground walking, high degrees of coordination were observed both in the controls and in the unaffected upper and the affected lower limbs of individuals with stroke.

An adaptation of interlimb coordination can be observed in individuals with stroke as a higher degree of the unaffected upper and the affected lower limb coordination when compared with that of the affected upper and unaffected lower limbs. A strategic pattern of using the unaffected upper limb movement for progression of walking seemed to be usually selected by individuals with stroke because it assisted the patients to swing their affected lower limb more easily. This implied that individuals with stroke used their unaffected upper limb to compensate for the affected lower limb movement when they walked.

A moderate degree of coordination between the affected shoulder and the unaffected hip in individuals with stroke was observed in the study. This increased when individuals with stroke walked at a fast speed. However, coordination of the unaffected shoulder and the affected hip in individuals with stroke and coordination of the shoulder and contralateral hip in the controls were not changed and presented with high degrees both at comfortable and fast gait speeds. Thus, gait speed is an important factor for improving coordination of the affected upper and the unaffected lower limbs. In contrast to a previous study, Stephenson and coworkers [18] did not find an improvement in interlimb coordination in individuals with stroke when the speed of walking was increased. However, it should be noted that the situation of treadmill walking may account for the different results.

Similar to a previous study [18], time lags were near zero both in controls and individuals with stroke. This zero time lags supported in-phase coordination of the upper and contralateral lower limbs as described in one study [27]. However, the motion presented in the affected upper limb during walking should be considered together with the muscle activation pattern since many factors, such as degree of spasticity and their synergistic pattern, can affect motion.

Table 3 Correlations of the shoulder and contralateral hip coordination and gait speed at comfortable and fast gait speeds.

Coordination	Comfortable gait speed		Fast gait speed	
	r_s	p	r_s	p
Individuals with stroke				
Unaffected shoulder and affected hip	0.730	0.001*	0.394	0.031*
Affected shoulder and unaffected hip	0.488	0.006*	0.612	0.001*
Controls				
Shoulder and contralateral hip	0.144	0.550	0.348	0.060

* Significant relationship at $p < 0.05$.
r_s = Spearman correlation coefficient.

Correlations between shoulder and contralateral hip coordination and gait speed

There was no significant correlation between the upper and contralateral lower limb coordination and gait speed in controls. This may result from a high degree of coordination in control individuals. In contrast, individuals with stroke demonstrated significant relationships between the upper and contralateral lower limb coordination and gait speeds. In the comfortable gait speed, we found a greater degree of correlation of speed with the coordination of the unaffected upper and affected lower limbs than the coordination of the affected upper and unaffected lower limbs. However, for the fast gait speed, correlation of speed and the upper and contralateral lower limb coordination showed opposite findings. This implies that speed of walking may affect the coordination of the affected upper and unaffected lower limbs.

Reduced arm movement amplitude could alter the frequency and phase relations between the arm and the leg. In natural walking speed, individuals with stroke who had upper limb dysfunction may walk slowly due to an atypical coordination between upper and lower limb motion [16]. In this case, the affected arm may hang passively while the unaffected arm compensates by moving more vigorously than expected. This explains why we found a compensatory pattern with a greater coordination between the unaffected shoulder and the affected hip angles during comfortable gait speed. In contrast to the fast gait speed condition, our results demonstrated a greater degree of coordination in the affected upper and unaffected lower limbs. This may be attributed to an adaptation of the affected upper limb in cooperation with the unaffected lower limb motion during the task of walking. It is noteworthy that most studies on gait pay greater attention to the lower limb rather than the upper limb.

Further study

In this study, gait speed was proven to affect the coordination between the upper limb and the contralateral lower limb. However, we assessed only two conditions of gait speed: comfortable and fast. We suggest that further studies be conducted focusing on slow gait speed so we may have a deeper understanding of the coordination between the upper limb and the contralateral lower limb.

Based on the physiology of the brain, lesions in the brain may affect upper and lower limb movements in different degrees. Therefore, coordination between the upper limb and the contralateral lower limb needs to be examined in individuals with stroke who have different lesions.

Conclusion

The present findings highlight an adaptive component of the upper and contralateral lower limb coordination in individuals with stroke. In individuals with stroke, better interlimb coordination was observed in the unaffected upper and affected lower limbs than in the affected upper and unaffected lower limbs in comfortable speed. Fast walking speed seems to improve the coordination of the affected upper and the unaffected lower limbs in individuals with stroke. We suggest that the key element of improving gait coordination be emphasized on the affected upper limb. In addition, gait training at a higher speed is likely to enhance interlimb coordination and improve gait performance.

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