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Neuromuscular and Biomechanical Strategies of Turning in Ambulatory Individuals Post-Stroke

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Abstract

Given that the inter-limb asymmetry and additional balance control are required for turning, stroke subjects spend more time to turn than healthy subjects. Few studies have investigated specific turning-related neuromuscular and biomechanical strategies post-stroke to clarify factors favoring or hindering turning speed toward different directions. The purpose of this study was to compare the speed and lower-limb muscular and kinematic strategies of turning between individuals with stroke and matched controls. Fifteen ambulatory individuals with chronic stroke and 15 matched healthy controls participated in this study. Turning speed during turning along a 0.8-meter radius curved path toward both sides for 5 meters was recorded. Simultaneously, kinematics and muscle activation patterns of lower extremity were measured by the joint angle and electromyography during turning. The slower speed was noted for the turning task in stroke patients when compared to controls. Individuals with stroke have insufficient muscle activation in tibialis anterior and biceps femoris of the affected inner leg, accompanied by reduced standing knee flexion, which disturb turning toward the affected side. The augmented standing knee flexion of unaffected side in stroke patients hindered the function of the outer leg while turning toward the affected side, but assisted the role of the inner leg while turning toward the unaffected side. However, the absence of difference in turning speeds toward the affected and unaffected sides may attribute to the diminished swing phase knee flexion of the affected outer leg. Our findings suggest that there are direction-related strategies in turning for stroke subjects since the inner and outer legs, respectively, have specific roles for standing support and leg swing during turning. Therefore, in addition to turning speed, kinematics and muscular components during turning toward either direction should be considered to improve turning performance as well as to prevent falls in stroke rehabilitation.

Key Words: electromyography, kinematics, stroke, turning

Introduction

Turning is an obligate sequence of motion during human locomotion in the daily living. Up to 40% of all steps taken in everyday walking are turns (9). However, turning is a challenging task and has been reported as one of the most frequent activities leading to falls for individuals with stroke (14). Falling while turning is eight times more likely to occur to lead to a hip fracture compared with walking straight. Moreover, most falls result from turning toward the affected side in subjects with stroke (6). Another

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significant post-stroke behavior is exemplified by the longer time required to turn (15). Nevertheless, most studies indicated the average time required to turn was not different whether the turns were made to the affected or the unaffected side in the participants with stroke (8, 20).

Previous studies have suggested that the descending command shapes the basic neuromuscular and biomechanical template for straight walking to achieve the needs of medial-lateral stability and side-dependent modulation imposed by turning (10). Kinematic analysis showed altered patterns of medial-lateral impulses during turning compared with straight walking (19). The impulses of inner and outer legs respectively shift the body toward the ipsilateral and contralateral limbs, which match the side of a curvilinear path. Unlike straight walking, the inner and outer legs need to achieve different functions during turning. Activity of muscles in medial compartments (gastrocnemius medialis, GM) and lateral compartments (biceps femoris, BF) show opposite modulations to generate body propulsion and to maintain increased needs of medial-lateral stability during turning (7). Side-specific modulation has also been demonstrated in the activity of tibialis anterior (TA) (5). As a result, the increased activity of TA in outer leg is associated with the longer swing phase of turning. In the inner leg, however, the increased muscle activity of TA is needed to dorsiflex the foot rapidly. During straight walking, muscle activity and joint coordination in individuals with stroke are reduced or are disordered in the affected leg, but such neuromotor control in the unaffected leg is similar to that observed in the healthy adults or is augmented to compensate the stroke-impaired and affected side. In addition to disorders of medial-lateral balance control, the above mentioned stroke-related asymmetric gait patterns may further affect the ability to turn and result in different strategies to turning toward the affected and unaffected sides in stroke subjects. The knowledge regarding the higher incidences of falls when turning toward the affected side compared to the unaffected side following stroke may thus be due to altered neuromuscular activity or strategy of lower extremity.

Given that the inter-limb asymmetry and additional balance control are required for turning, turning speed was compromised in stroke subjects as compared with healthy subjects. Although the turning speed was not different whether the turns were made to the affected or unaffected side in the participants with stroke, most falls resulting from turning occurred toward the affected side. We, therefore, hypothesized that individuals with stroke showed slower turning speed as compared with the matched controls. Furthermore, there were distinct lower-limb muscular and kinematic patterns of turning when an individual with stroke made turns toward the affected and unaffected side.

Materials and Methods

Participants

Fifteen participants who had suffered stroke were recruited from the community and medical centers in Taipei city, Taiwan. The diagnosis, age, gender, type of stroke, side of lesion, duration of hemiparesis and activities of daily living function (Barthel index) were obtained from patient interviews and medical charts. Balance performance was assessed by the Berg Balance Scale (1). The basic features of straight walking, speed and temporal asymmetry index were obtained from the GAITRite system (CIR system, Inc., Havertown, PA, USA) (18). Gait speed indicates the overall gait function (21). The temporal asymmetry index reflects the temporal difference of weight bearing between two legs and is associated with the challenged balance control (21), and was calculated using the following formula (16).

Temporal asymmetry index

$$= \left| 1 - \frac{\text{single support time (affected)}}{\text{single support time (unaffected)}} \right|$$

The single support time was quantified as the time during each stride when only one foot was in contact with the ground.

To be included in the study, participants with stroke had to satisfy the following criteria: [1] diagnosis of first-ever stroke with unilateral motor deficits for at least 6 months, [2] ability to walk independently for at least 6 meters (m) with or without the use of walking aids, and [3] ability to follow verbal instructions. The exclusion criteria were: [1] unstable medical conditions (*e.g.*, deep vein thrombosis, aspiration pneumonia or superimposed sepsis), and [2] history of other diseases known to interfere with participation in the study (*e.g.*, heart failure, hemi-neglect, or diabetic neuropathy).

Fifteen healthy subjects matched by age and gender were also recruited from the community as controls. The participants had no history of medical problems affecting their balance and walking performance. This study was approved by the Institutional Review Board of Mackay Memorial Hospital and was explained to the participants prior to the study to obtained informed consent.

Experimental Protocol

In this study, participants were asked to walk

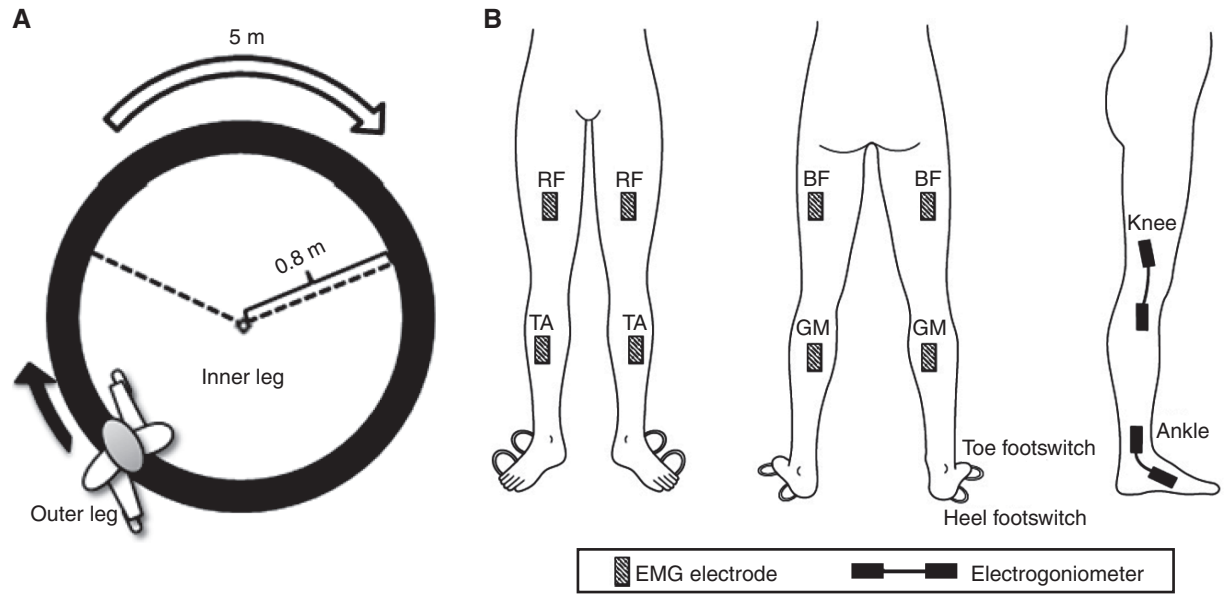

Fig. 1. (A) Schematic of the walkway used for turning task. (B) Placement of electrogoniometers, surface EMG electrodes and footswitches. (Abbreviations, RF: rectus femoris; BF: biceps femoris, TA: tibialis anterior, GM: gastrocnemius medialis)

without using any walking aids or wearing orthosis along a 5-m circumference curved path, with a radius of 0.8 m for the turning performance (Fig. 1A). Turning speed was measured by a stopwatch. Kinematic and electromyographic (EMG) data were simultaneously obtained using the BIOPAC MP150WMW System and AcqKnowledge software (BIOPAC System Inc., Goleta, CA, USA), with a sampling rate of 1,000 Hz. The speed, kinematic and EMG data of turning toward the affected and unaffected sides in the stroke group was matched to the non-dominant and dominant sides, respectively, in the control group. Leg dominance of healthy subjects was determined by the ball-kick test (12). The leg used to kick the ball was identified as the dominant leg.

Measurements

Turning Speed

The participants were asked to perform the turning at a comfortable speed three times in each direction in random order. Time needed to complete turning along a defined curved path was recorded, and the average of three trials was used for data analysis. The speed was derived from dividing the distance by the time (3). The intra-rater reliability for turning speed was 0.98 toward the non-dominant side and 0.99 toward the dominant side of healthy adults in our pilot work.

Kinematics

Four electrogoniometers (Biometrics Ltd, Ladysmith, VA, USA) were placed on the knee and ankle joints of each leg (Fig. 1B) to measure joint angles during walking. The electrogoniometer had two end blocks: a telescopic and a fixed end block, joined by an instrumented spring with a strain gauge (22). For measuring the knee-joint angle, the fixed end block paralleled with the line of the greater trochanter and lateral epicondyle of the femur, and the telescopic end block paralleled with the line of the lateral malleolus and lateral epicondyle (16). For measuring the ankle-joint angle (22), the fixed end block paralleled with the line of the fifth metatarsal head and lateral malleolus, and the telescopic end block paralleled with the line of the head of fibula and lateral malleolus (16). Six peak values of joint angles, the first and second peak knee flexion, the first and second peak ankle plantarflexion, and the first and second peak ankle dorsiflexion (Fig. 2), during each gait cycle were calculated offline.

FlexiForce footswitches (Tekscan, Boston, MA, USA) placed beneath each heel were used to identify heel strikes for time normalization of the kinematic data (Fig. 1B and Fig. 2) (13). The gait cycle was defined as the time interval between two successive heel strikes of one leg.

EMG

The skin was shaved and cleaned with alcohol swabs before applying the 11-mm Ag-AgCl surface electrodes (BIOPAC System Inc.) for recording EMG. Surface EMG from the following muscles was recorded in each leg: rectus femoris (RF), BF, TA and GM

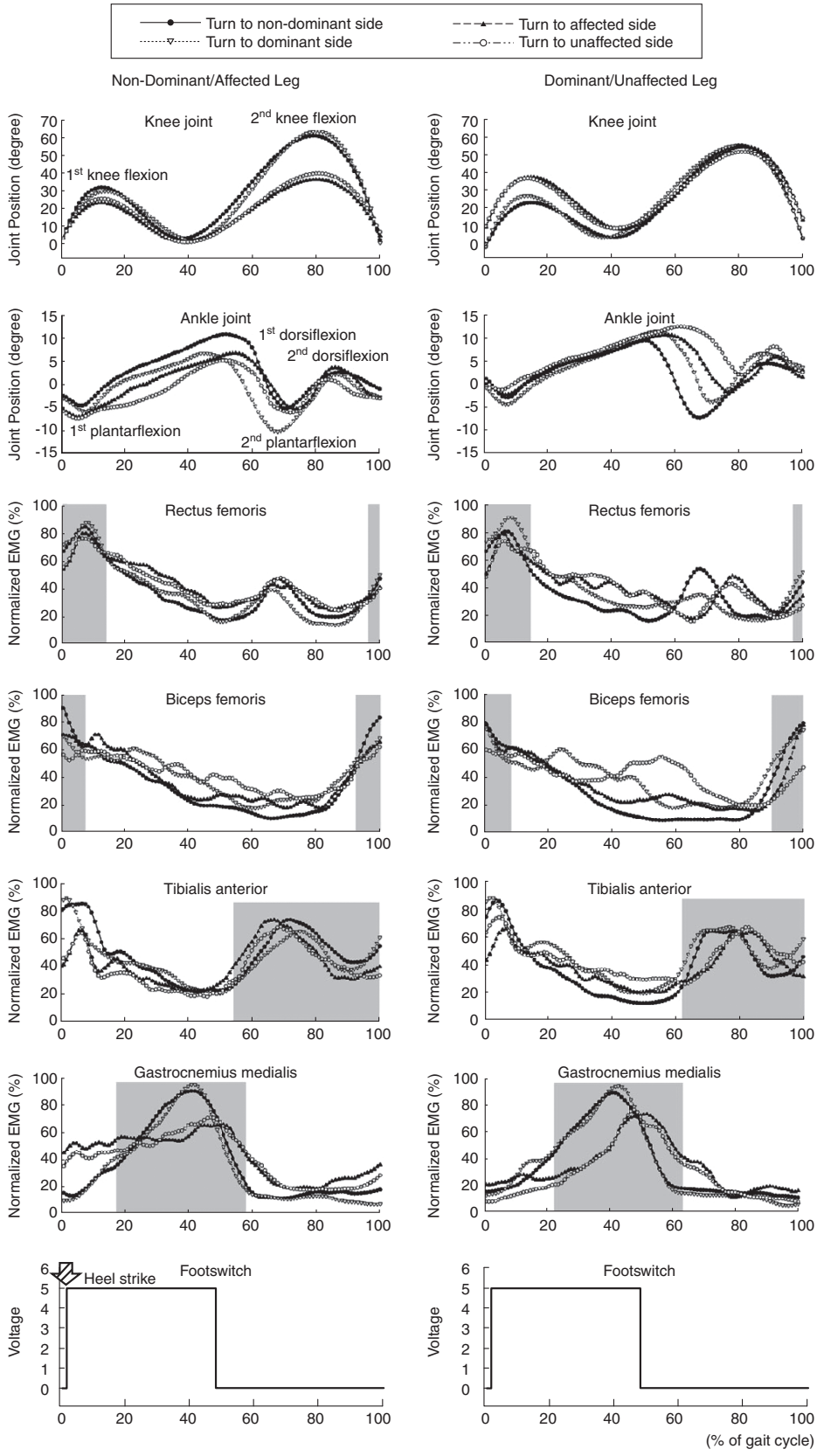

Fig. 2. Pooled kinematic data (position profile) and normalized EMG data (linear envelope profile) of non-dominant/affected (left panel) and dominant/unaffected legs (right panel) over the normalized (100%) gait cycle in match controls and stroke participants. Gray-shaded areas indicate the given time interval in which EMG amplitude was computed for subsequent analysis. The onset of footswitch indicate the beginning of one gait cycle.

Table 1. Basic data of the participants

	Control group (n = 15)	Stroke group (n = 15)	*P**
Sex (male/female)	12/3	12/3	1.0
Age (years)	61.9 ± 9.0	61.2 ± 12.6	0.887
Height (cm)	162.5 ± 7.8	166.2 ± 4.5	0.153
Weight (kg)	62.0 ± 10.6	70.9 ± 12.3	0.060
Dominant leg (right/left)	13/2	13/2	1.0
Side of hemiparesis (right/left)	–	7/8	–
Type of stroke (hemorrhagic/ischemic)	–	8/7	–
Time post-stroke (years)	–	4.8 ± 4.2	–
Barthel index		80.3 ± 9.2	–
Berg Balance Scale (total: 56)	55.9 ± 0.4	50.4 ± 5.5	0.004
Walking speed during straight walking (m/s)	1.3 ± 0.2	0.7 ± 0.3	< 0.001
Temporal asymmetry index during straight walking	0.0 ± 0.0	0.2 ± 0.1	0.001

Values are mean ± standard deviation. **P*-values for control and stroke group comparisons.

(Fig. 1B). Electrode placements for these muscles were in accordance with the recommendations from the SENIAM project (Surface ElectroMyoGraphy for the Non-Invasive Assessment of Muscles) (11). All EMG data were band-pass filtered (40-400 Hz) and full-wave rectified (23). Then, a second-order Butterworth low-pass filter, with a cutoff frequency of 9 Hz, was used to produce a linear envelope representation (2). Footswitch data were used for time normalization. Each subject's ensemble average was normalized to the peak of the subject ensemble average for amplitude normalization (24). The amplitude of muscle bursts during each gait cycle was computed by integrating the activity of each individual EMG burst during the time interval (onset-offset) defined during each walking trial, as described below. Onset and offset of the EMG burst were established at points in which the muscle activity exceeded and fell below the mean activity, respectively, plus three standard deviations were recorded during a period when these muscles were least active (5). The amplitudes of RF, BF and GM (A_{RF}, A_{BF}, and A_{GM}) from onset to offset of bursts were calculated. The amplitude of TA (A_{TA}) was calculated from the onset of burst to the end of the swing phase.

Statistics

All data were analyzed using SPSS version 16.0 statistical software (SPSS Inc., Chicago, IL, USA). Descriptive statistics are expressed as means ± standard deviations for all variables. Intergroup differences among baseline characteristics were evaluated using an independent *t*-test or χ^2 analysis. To investigate the turning performance and strategies on neuromuscular and biomechanical aspects of turning post-stroke, we compared turning speed and lower-limb muscular and kinematic patterns of turning between individuals with stroke and matched controls in both turning directions, respectively. Data from the affected leg of stroke participants were compared with the non-dominant side of the controls, and data from the unaffected leg of stroke participants were compared with the dominant side of the controls. The comparisons of turning speed, range of knee and ankle, and EMG amplitude of each muscle between the control group and stroke group were analyzed by independent *t*-tests for intergroup comparisons. The comparisons in speed between turning directions were further analyzed by paired *t*-test for intragroup comparisons. Due to the fact that the comparisons were made for the non-dominant/affected and dominant/unaffected sides, respectively, the statistical significance was corrected to $P < 0.025$.

Results

Characteristics of Participants

Fifteen stroke participants (12 males and 3 females) were assessed with a mean age of 61.2 ± 12.6 years and were 4.8 ± 4.2 years post stroke (Table 1). Considering the age and gender, 15 matched subjects (12 males and 3 females) with a mean age of 61.9 ± 9.0 years were assessed. As compared to the matched controls, stroke subjects had poorer balance performance (Controls: 55.9 ± 0.4, Stroke: 50.4 ± 5.5; $P = 0.004$). Stroke subjects also walked slower (Controls: 1.3 ± 0.2 m/s, Stroke: 0.7 ± 0.3; $P < 0.001$) and showed higher asymmetric temporal index (Controls: 0.0 ± 0.0, Stroke: 0.2 ± 0.1; $P = 0.001$) during straight walking.

Turning Speed

Stroke subjects walked significantly slower than

Table 2. Kinematic and electromyographic characteristic of affected legs

	Turning toward the affected side (Affected leg is inner leg)			Turning toward the unaffected side (Affected leg is outer leg)		
	Control group	Stroke group	*P**	Control group	Stroke group	*P**
Joint Angles (degree)						
1st peak knee flexion	31.4 ± 7.5	22.2 ± 10.6	**0.017**	29.7 ± 8.8	24.3 ± 9.7	0.152
2nd peak knee flexion	60.0 ± 8.0	34.2 ± 14.6	**< 0.001**	60.5 ± 5.8	37.0 ± 15.3	**< 0.001**
1st peak ankle plantarflexion	-4.8 ± 3.6	-7.3 ± 6.1	0.239	-6.3 ± 2.5	-7.6 ± 6.4	0.509
1st peak ankle dorsiflexion	10.8 ± 2.8	6.7 ± 4.7	**0.011**	6.8 ± 3.6	5.2 ± 4.6	0.342
2nd peak ankle plantarflexion	-5.4 ± 4.7	-5.4 ± 7.4	0.981	-10.1 ± 5.6	-6.4 ± 7.7	0.179
2nd peak ankle dorsiflexion	5.6 ± 4.0	3.7 ± 5.0	0.295	2.3 ± 3.8	1.1 ± 5.5	0.513
Electromyographic Amplitudes (%)						
Rectus femoris	40.5 ± 9.8	36.8 ± 8.1	0.317	43.6 ± 9.6	35.4 ± 7.3	**0.021**
Bicep femoris	48.5 ± 9.6	38.0 ± 11.4	**0.018**	37.7 ± 12.1	33.0 ± 0.09	0.304
Tibialis anterior	77.4 ± 6.3	62.9 ± 14.9	**0.005**	73.4 ± 9.0	63.7 ± 15.0	0.061
Gastrocnemius medialis	85.8 ± 7.6	80.0 ± 7.4	0.061	87.8 ± 4.4	83.2 ± 9.3	0.119

Values are mean ± standard deviation. **P*-values for control and stroke group comparisons.

did the control subjects while performing the turning toward the affected side (Controls: 1.0 ± 0.2 m/s, Stroke: 0.6 ± 0.2 m/s; $P < 0.001$) and unaffected side (Controls: 1.0 ± 0.2 m/s, Stroke: 0.5 ± 0.2 m/s; $P < 0.001$). In addition, for the stroke group, the speed of turning toward the affected side was not different from that toward the unaffected side ($P = 0.28$). Similar results were found in the control group, where no differences were noted between the non-dominant and dominant sides ($P = 0.08$).

Kinematics of Turning

Kinematic characteristics of the affected leg are shown in Table 2. Compared with the matched healthy subjects, participants with stroke decreased the second peak knee flexion of the affected leg whether the turns were made to the affected side (Controls: 60.0 ± 8.0°, Stroke: 34.2 ± 14.6°; $P < 0.001$) or to the unaffected side (Controls: 60.5 ± 5.8°, Stroke: 37.0 ± 15.3°; $P < 0.001$). In addition, participants with stroke decreased the first peak knee flexion (Controls: 31.4 ± 7.5°, Stroke: 22.2 ± 10.6°; $P = 0.017$) and first peak ankle dorsiflexion (Controls: 88.9 ± 2.8°, Stroke: 84.7 ± 4.7°; $P = 0.011$) of the affected leg while turning to the affected side as compared with the controls.

Kinematic characteristics of the unaffected leg are shown in Table 3. Compared with the matched healthy subjects, participants with stroke increased the first peak knee flexion of the unaffected leg whether the turns were made to the affected side (Controls: 22.1 ± 6.5°, Stroke: 34.3 ± 9.8°; $P < 0.001$) or to the unaffected side (Controls: 26.5 ± 6.4°, Stroke: 34.09 ± 9.1°; $P = 0.021$).

There were no other significant differences in kinematic characteristics between the stroke and control groups.

EMG of Turning

The EMG characteristics of the affected leg are shown in Table 2. Compared with the matched healthy subjects, participants with stroke decreased the A_{BF} (Controls: 48.5 ± 9.6%, Stroke: 38.0 ± 11.4%; $P = 0.018$) and A_{TA} (Controls: 77.4 ± 6.3%, Stroke: 62.9 ± 14.9%; $P = 0.005$) of the affected leg while turning to the affected side. On the other hand, participants with stroke decreased A_{RF} of the affected leg while turning to the unaffected side as compared with the controls (Controls: 43.6 ± 9.6%, Stroke: 35.4 ± 7.3%; $P = 0.021$).

The EMG characteristics of the unaffected leg are shown in Table 3. Compared with the matched healthy subjects, participants with stroke decreased the A_{RF} and A_{TA} of the unaffected leg whether the turns were made to the affected side (A_{RF}, Controls: 42.7 ± 7.7%, Stroke: 34.1 ± 7.1%; $P = 0.007$; A_{TA}, Controls: 70.8 ± 9.1%, Stroke: 61.5 ± 9.5%; $P = 0.019$) or to the unaffected side (A_{RF}, Controls: 44.8 ± 11.8%, Stroke: 33.2 ± 5.7%; $P = 0.005$; A_{TA}, Controls: 80.1 ± 4.8%, Stroke: 63.2 ± 8.6%; $P < 0.001$). In addition, participants with stroke decreased the A_{BF} of the unaffected leg while turning to the affected side as compared with the controls (Controls: 40.9 ± 10.6%, Stroke: 28.4 ± 8.7%; $P = 0.003$).

There were no other significant differences in EMG characteristics between the stroke and control groups.

Discussion

Slower speed was noted for the turning task in stroke subjects when compared to controls matched by age and gender. Specifically, our data suggest that

Table 3. Kinematic and electromyographic characteristic of unaffected legs

	Turning toward the affected side (Unaffected leg is outer leg)			Turning toward the unaffected side (Unaffected leg is inner leg)		
	Control group	Stroke group	*P**	Control group	Stroke group	*P**
Joint Angles (degree)						
1st peak knee flexion	22.1 ± 6.5	34.3 ± 9.8	**< 0.001**	26.5 ± 6.4	34.09 ± 9.1	**0.021**
2nd peak knee flexion	53.2 ± 4.1	53.9 ± 8.1	0.799	54.0 ± 5.1	51.2 ± 9.4	0.362
1st peak ankle plantarflexion	-3.8 ± 3.4	-2.5 ± 6.9	0.561	-4.8 ± 5.0	-1.4 ± 6.6	0.144
1st peak ankle dorsiflexion	9.5 ± 4.3	10.7 ± 5.8	0.562	11.8 ± 4.3	12.4 ± 5.5	0.779
2nd peak ankle plantarflexion	-7.4 ± 7.1	-2.3 ± 6.8	0.072	-4.0 ± 5.8	1.0 ± 6.1	0.044
2nd peak ankle dorsiflexion	4.5 ± 4.6	6.1 ± 5.1	0.409	6.8 ± 4.8	8.9 ± 4.6	0.270
Electromyographic Amplitudes (%)						
Rectus femoris	42.7 ± 7.7	34.1 ± 7.1	**0.007**	44.8 ± 11.8	33.2 ± 5.7	**0.005**
Bicep femoris	40.9 ± 10.6	28.4 ± 8.7	**0.003**	49.6 ± 12.8	40.0 ± 11.2	0.052
Tibialis anterior	70.8 ± 9.1	61.5 ± 9.5	**0.019**	80.1 ± 4.8	63.2 ± 8.6	**< 0.001**
Gastrocnemius medialis	89.0 ± 5.3	79.6 ± 18.0	0.094	84.5 ± 5.5	80.7 ± 13.2	0.355

Values are mean ± standard deviation. **P*-values for control and stroke group comparisons.

individuals with stroke have insufficient recruitments in A_{TA} and A_{BF} of the affected inner leg, accompanied by reduced standing knee flexion, which disturbs turning toward the affected side. The augmented standing knee flexion of the unaffected side in stroke patients hindered the function of the outer leg while turning toward the affected side, but assisted the role of the inner leg while turning toward the unaffected side. However, the absence of difference in turning speed toward the affected and unaffected side may attribute to the diminished swing phase knee flexion of the affected outer leg.

Turning is a challenging task for stroke subjects due to inter-limb asymmetry and additional balance control required for turning. Greater time required to turn was correlated to poor balance performance and temporal gait asymmetry. Thus, it is not surprising to note that our stroke participants, demonstrating impaired balance ability, asymmetric gait pattern and slower speed during straight walking, turned slower than the control group. Previous studies suggested the A_{RF} was decreased or unchanged while turning as compared with straight walking (5, 7), and the RF is the speed-dependent muscle. Therefore, the decreased A_{RF}, regardless of the turning directions, may have resulted from the slower turning speed in our stroke subjects as compared with the controls. On the other hand, the typical hemiplegic gait, known as the shorter single support time of the affected leg and consequently shorter swing time of the unaffected leg, also caused the decreased A_{TA} of the unaffected leg during turning toward either direction.

Symmetric temporal features during straight walking are changed in turning (5). The longer swing duration allows the outer leg to counteract the discrepancy in the stride length of the inner and outer legs. The longer stance duration of the inner leg is related to the tendency of whole-body tilt toward the turning direction. After stroke, the disordered neural drive encoding for the temporal template of turning results in disturbed joint coordination especially around the bilateral knee (4), but these impairments exert impact on the two turning directions in different ways since the inner and outer legs naturally have specific roles during turning. While turning toward the affected side, the augmented knee flexion of the unaffected outer leg in the stance phase could contribute to greater support, but could also cause a decreased vertical distance between the pelvic and floor. This compensate strategy is opposite to the inward tendency of body tilt normally required for turning. Concurrently, the restricted range of the ankle dorsiflexion in the pre-swing phase and the knee flexion in the swing phase of the affected inner leg might affect the foot clearance during turning. The combinations of these two features may increase the risk of falls during turning toward the affected side. In view of the turns made toward the unaffected side, increased peak knee flexion of the unaffected inner leg in the stance phase generate higher stability in accordance with the inward tendency of body tilt (3, 5). This strategy favors the possible faster turning speed toward the unaffected side. Unfortunately, diminished peak knee flexion of the affected outer leg in the swing phase may result in shorter step length and thus hindered the turning speed toward the unaffected side. Taking together, this may explain why the average time needed to turn to either direction was not significantly different in our participants with stroke (3, 5).

During normal turning, the increased A_{TA} in the outer leg can be explained by the longer swing phase, whereas the increase A_{TA} in the inner leg was due to

the need of rapid ankle dorsiflexion (7). We observed the impaired control of the affected leg - decreased A_{TA} and limited ankle dorsiflexion in stroke subjects was shown during turning toward the affected side, but not toward the unaffected side. The corticospinal drive to affected inner or outer leg for generating turning seems to be selectively affected in these chronic stroke subjects. We speculate that the longer swing phase of the affected leg (20), known as the disturbing feature during straight walking, may have positive effects for turning to the unaffected side, because the swing duration in the outer leg was longer to allow more time to travel longer distance imposed by the turning. Despite that insufficient muscle strength of dorsiflexors is the common deficit post-stroke (16), the TA of the affected side could generate sufficient dorsiflexion to achieve the role for the affected outer leg due to relatively longer period to activate the muscle while turning toward the unaffected side. Under time constraint, however, stroke subjects fail to recruit enough A_{TA} of the affected side to fulfill the role of the inner leg when turning toward the affected side. The association of deficit in the TA and falls incidence has been identified in stroke subjects (17). It might further explain the higher falls incidence occurred while turning toward the affected side.

Concurrently decreased A_{BF} and first peak knee flexion of the affected inner leg were the other two disturbing factors while turning toward the affected side. A recent study has suggested that A_{BF} (posterolateral muscles) of the inner leg tends to increase, whereas the A_{GM} (posteromedial muscles) of the outer leg tends to increase as path curvature increases (7). Our data showed that A_{BF} of affected inner leg decreased, which does not favor modulation of the inner leg during turns in stroke subjects. Similar to the present findings, the same study (7) suggested that lowered flexibility of neural comments after stroke could contribute to reduced modulation patterns to adapt to the increasing balance challenge in the medial-lateral plane emerged during turning, as the body center of mass was compelled to shift toward the direction of turning (19). In addition, the flexed-knee strategy during the loading response phase of the gait, which lowers the center of mass to increase the stability and to facilitate trunk rotation for turning in older adults (3), was absent in stroke subjects. The coordinated stability-related muscle synergies and kinematic template in the inner leg during turning is compromised after stroke which may explain the greater occurrence of falls during turning toward the affected side as compared with the unaffected side.

Several limitations need to be noted in this study. First, the small sample size may limit generalizations of our results. Second, the fall histories of the stroke patients during walking and turning were not obtained in the current study, but warrant further studies to assess the turning strategies in stroke patients with fall history. Furthermore, the frontal and transverse plane kinematics should also be considered to fully present the turning task.

We described possible strategies as noted by kinematic and muscular data to elucidate the slower turning speed in the stroke participants as compared to controls. Although stroke subjects had difficulties to clear the foot and failed to bear the weight sufficiently in the affected inner leg while turning toward the affected side, inadequate range of knee in the affected outer leg also hindered the turning performance when turns were made toward the unaffected side. These changes implied higher falling risks when turning toward the affected side, however, with no difference in turning speed between two directions. Our findings highlight the roles of inner and outer legs of turning by providing knowledge of neuromuscular and biomechanical strategies post-stroke. In addition to the speed of turning, kinematics and muscular components during turning toward either direction should also be considered to improve turning performance as well as to prevent falls in stroke rehabilitation.

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