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Spatial and Temporal Features of Motor Modules in an individual with Hemiparesis During the Curvilinear Gait: A Pilot Single-Case Study

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Abstract

Purpose: This study aimed to investigate spatial and temporal features of motor control in an individual with hemiparesis during the curvilinear gait (CG) and proposed an exercise guideline. **Research design, data and methodology:** An individual aged 63 with hemiparesis by stroke disease was participated in the study. Autoencoder (AE) was used to extract four motor modules from eight muscle activities of the paretic leg during CG. After extraction, each module of four modules was operationally defined by numbering from M1 to M4 according to spatial and temporal features and compared with results reported in a previous study. **Results:** As a result, an individual with hemiparesis had motor module problems related to difficulty of weight acceptance (module 1), compensation for the weakness of ankle plantar flexor (module 2), a spastic synergistic pattern (module 3) and difficulty with transition from the swing to stance phase (module 4) in terms of spatial features. Also, a delayed activation timing of temporal motor module (module 2) related to the forward propulsion during CG was observed. **Conclusions:** Gait rehabilitation for the stroke will need to consider clinical significances in respect of the deterioration of motor module and provide the tailored approaches for each gait phase.

Keywords : Autoencoder, Curvilinear gait, Motor Modules, Stroke

JEL Classification Codes : I10, I30, I31

1. Introduction

Curvilinear gait (CG) is so essential for independent locomotion such as freely direction switching during forward progression. Furthermore, CG requires higher levels of motor control and the well-coordinated muscle activation (Courtine & Schieppati, 2003; Imai, Moore, Raphan & Cohen, 2001) that is associated with the risk of falling in patients with neurological disorder (Hyndman, Ashburn & Stack, 2002; Harris, Eng, Marigold, Tokuno, & Louis, 2005). Especially, many studies have been already reported neuromuscular control problems by hemiplegia in

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stroke population such as gait asymmetry and slow gait speed (Kirker, Jenner, Simpson, & Wing, 2000; Sousa, Silva & Santos, 2015; Rozanski, Huntley, Crosby, Schinkel-Ivy, Mansfield, & Patterson, 2020). Therefore, further in-depth observations to post-stroke motor control changes during CG, understandably, would be unavoidable.

2. Literature Review

From biomechanical perspective, during CG, each leg plays an independent functional role (Courtine & Schieppati, 2003; Courtine, Papaxanthis, & Schieppati, 2006). Therefore, stoke patients with a prominently reduced capacity of the coordinated muscle activation in lower extremity must have the decrease in gait speed and the abnormal shift of central of pressure (COP) during CG (Chisholm, Qaiser, & Lam, 2015; Duval, Luttin, & Lam, 2011). Ironically, despite long-term investigation on motor control changes during post-stroke gait has been progressed so far, with respect to CG, fragmentary findings of motor control changes in muscle activation and few clinical implications were reported.

Muscle coordination is worked by central nervous system that optimize motor control by minimizing the number of control signals, called motor modules in this study. Several computational dimensional reduction techniques have been introduced imitating this concept so far (Hirashima & Oya, 2016; Buongiorno, Cascarano, Camardella, De Feudis, Frisoli, & Bevilacqua, 2020). Through these analysis methods, features of motor modules in patients and rehabilitation methods were suggested (Hassan, Kadone, Ueno, Hada, Sankai, & Suzuki, 2018; Lim, Lim, Lee, Sim, Chang, Yoon, & Jung, 2021). Most of studies reported that 4 to 6 motor modules were observed in the healthy during rectilinear gait while patients with neurological impairment showed decrease in the number of modules due to the merging of modules (Clark, Ting, Zajac, Neptune, & Kautz, 2010). However, except for a recent study examined spatiotemporal features of motor modules for the healthy during SW and CG (Bejarano, Pedrocchi, Nardone, Schieppati, Baccinelli, Monticone, & Ferrante, 2017), there were still few studies to examine features of motor modules during CG in the stroke patients.

Therefore, this study was aimed to demonstrate features of motor modules extracted by autoencoder, machine learning technique in stroke patients and discuss the differences when compared with the healthy motor modules, which was recently reported by a previous study (Bejarano et al., 2017).

3. Methodology

3.1. Participants

A male patient with hemiplegia aged 63 was participated in this single-case study. In addition to history of disease, Berg balance test (BBS), Fugl-Meyer assessment (FMA) and Timed up & Go test (TUG) were assessed for the demographics of the patient. The study was approved by the Institutional Review Board of the Korea University (KUIRB2018-0127) and written informed consent was obtained from each participant.

3.2. Experimental procedure

The participant performed 20 cycles of the curvilinear gait (CG) at a self-selected speed on circular path, drawn with tape on flat floor as depicted in **Figure 1**. He performed a 20-cycle CG task with the paretic leg located at outside of the circular path (OCG) and then, did in the opposite direction (ICG). The participant was checked consistently to give the rest time for safety.

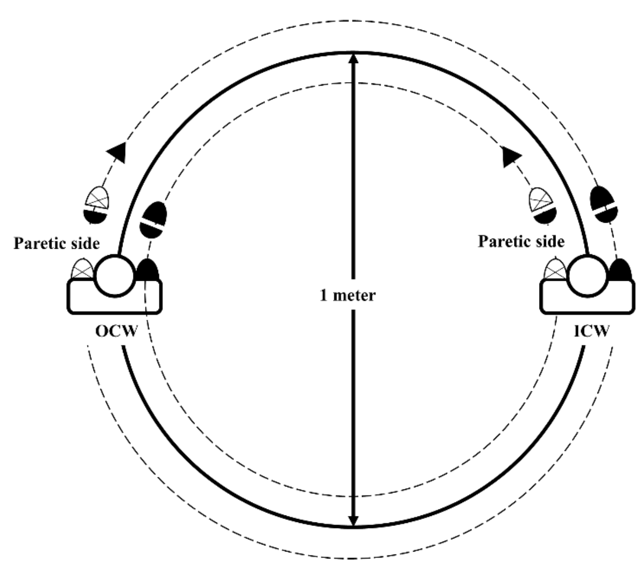

Figure 1: Depiction of the curvilinear gait (CG) task that a participant performed in this study

While he performed the tasks, surface electromyography (EMG) (Noraxon Telemyo DTS, USA) was measured on eight lower extremity muscles as depicted in **Table 1**.

Table 1: Eight lower extremity muscles measured by surface electromyography

Muscles	EMG sensor location
Rectus Femoris	50% on the line from the anterior spina iliac superior to the superior part of the patella
Adductor Longus	3/4 inches distal to pubic tubercle over the bulk of the adductor muscles
Vastus Medialis	80% on the line between the anterior spina iliaca superior and the joint space in front of the anterior border of the medial ligament
Tibialis Anterior	1/3 on the line between the tip of the fibula and the tip of the medial malleolus
Gluteus Maximus	50% on the line between the sacral vertebrae and the greater trochanter
Biceps femoris	50% on the line between the ischial tuberosity and the lateral epicondyle of the tibia
Semitendinosus	50% on the line between the ischial tuberosity and the medial epicondyle of the tibia
Gastrocnemius	the most prominent bulge of the muscle

EMG signals were sampled at 1000Hz and a band-pass filter at 20-750Hz. The skin preparation to minimize the effect of signal noises and artifacts was conducted before EMG electrodes were attached. After data collection, all data were again filtered by a high-pass filter (35 Hz, fourth-order Butterworth filter), rectification and a low-pass filter (5 Hz, fourth-order Butterworth filter).

Then, the filtered data was segmented into 20 cycles per cycle and interpolated to 200 time-points. Next, the data of each cycle was normalized to the peak value of each muscle. Finally, all normalized data were concatenated as the input data for autoencoder, consisted of 4000 data points (20 cycles × 200 points) per muscle.

3.3. Motor module Extraction by Autoencoder

Undercomplete autoencoder (AE) is recently introduced as one of methods for motor module extraction (Buongiorno et al., 2020). 20-cycle concatenated data of eight muscles was used for an input data of AE algorithm and it extracted output data which resembled the input original data the most. Two types of features in motor module extracted by autoencoder were called spatial feature and temporal feature, respectively. Spatial motor module indicates the weighted specific muscle group, composed of an individual module and temporal motor module indicated the time-varying activity of an individual module.

Prior to motor module extraction, the extracting number of modules was set to 4, which was the same number with results of a previous study that finally enable to compare between the results of this study and previous study. Additionally, after extraction, the peak timing of each temporal motor module was calculated and expressed as the percentage of gait cycle.

3.4. Quality of data reconstruction of four motor modules

Variance of accounted for (VAF) was used to evaluate the reconstruction quality of extracted four motor modules by the following equation:

$$\text{VAF} = \left(1-\frac{\sum_{i=1}^{muscle}\sum_{j=1}^{time}(EMG_{raw}(i,j)-EMG_{reconstucted}(i,j))^2}{\sum_{i=1}^{muscle}\sum_{j=1}^{time}(EMG_{raw}(i,j))^2}\right) \text{ x } 100$$

4. Results

4.1. Demographics of the participant

The patients had the gait disorder for 6 years since onset of hemiplegia by stroke disease due to brain hemorrhage. Motor impairment severity was scored 70 which was in a range of mild (> 56 scores). The rest of detailed demographics was shown in **Table 2**.

Table 2: The detailed demographic of the participant

Sex	Age (years)	Heights (cm)	Weights (kg)	Type of stroke	Onset (year/month)	Walking speed (m/s)	BBS	FMA
M	63	169	59	Left side of. BG, ICH and IVH	2016/05	23	38	70

Note: BBS: Berg Balance Scale; BG: Basal Ganglia; FMA: Fugl-Meyer Assessment; ICH: Intracerebral hemorrhage; IVH: Intraventricular hemorrhage

4.2. Definition of motor modules

After extracting four motor modules using autoencoder, each motor module was numbered according to its spatial and temporal feature that was also reported in previous studies. Extracted spatial and temporal features of motor modules during OCG and ICG was depicted in **Figure 2 and 3**.

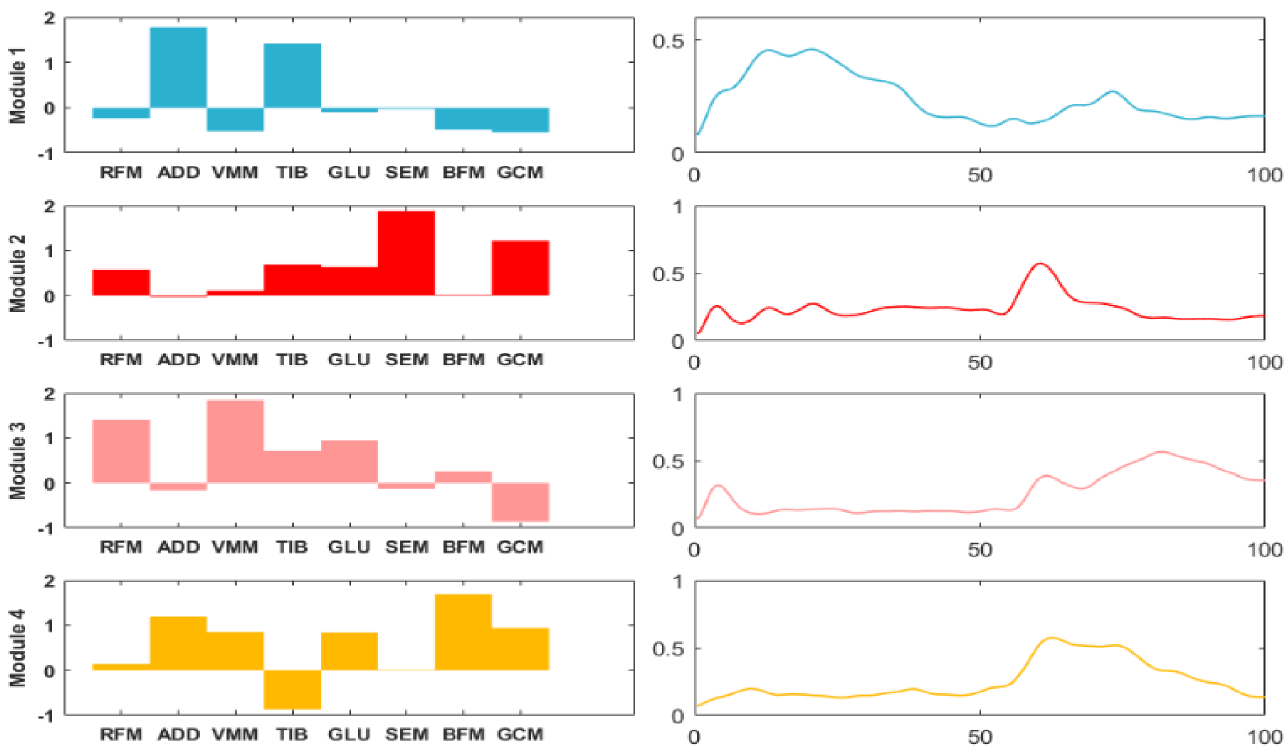

Figure 2: Extracted spatial and temporal features of motor modules during OCG

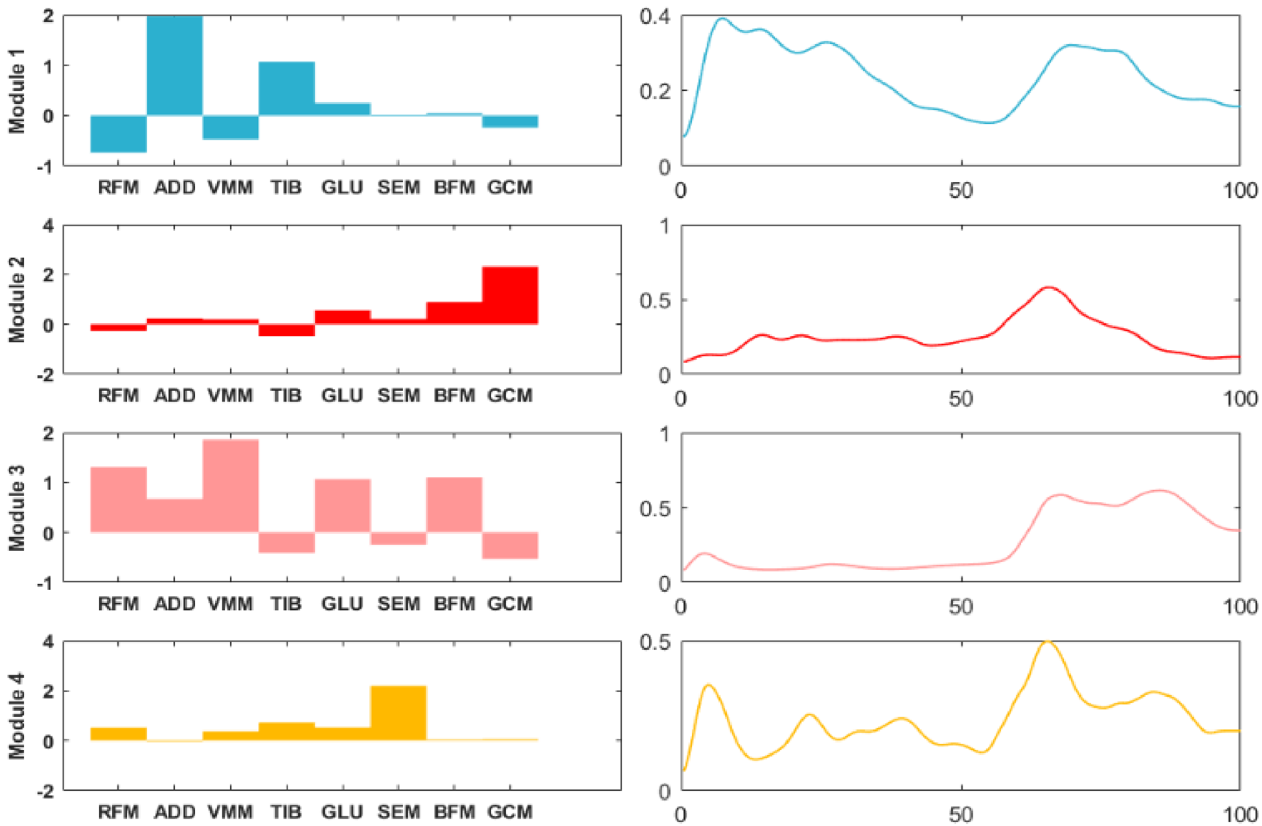

Figure 3: Extracted spatial and temporal features of motor modules during ICG

The concrete values of spatial features were shown in **Table 3**.

Table 3: The spatial motor modules in the participant during the curvilinear gait

Modules	OCG				ICG			
	M1	M2	M3	M4	M1	M2	M3	M4
RFM	-0.23	0.58	1.40	0.14	-0.73	-0.27	1.31	0.51
ADD	1.78	-0.03	-0.16	1.20	1.97	0.24	0.68	-0.04
VMM	-0.51	0.10	1.84	0.85	-0.47	0.20	1.86	0.38
TIB	1.42	0.69	0.71	-0.87	1.07	-0.47	-0.41	0.73
GLU	-0.09	0.63	0.94	0.84	0.25	0.55	1.07	0.52
SEM	-0.03	1.89	-0.13	0.01	-0.02	0.21	-0.24	2.20
BFM	-0.48	0.02	0.25	1.70	0.04	0.89	1.11	0.04
GCM	-0.54	1.22	-0.86	0.94	-0.24	2.31	-0.53	0.05

Note: Values are presented as the weighting coefficients of all muscles in each module. OCG: Paretic leg located at outside of the curve during curvilinear gait; ICG: Paretic leg located at inside of the curve during curvilinear gait. Abbreviation of muscles: ADL: Adductor longus, BFM: Biceps femoris, GC: Gastrocnemius, GM: Gluteus maximus, RF: Rectus femoris, ST: Semitendinosus, TA: Tibialis anterior, VM: Vastus medialis

Features of each motor module was as follows: **module 1 (M1)** was characterized by spatial features of hip and knee extensor (VMM and GLU), and ankle dorsiflexor (TIB) and temporal features for early stance phase; **module 2 (M2)** was characterized by spatial features of ankle plantar flexor (TIB) and temporal features for mid to late stance phase; **module 3 (M3)** was characterized by spatial features of hip flexor (RFM) and adductor (ADD) and temporal features of early swing phase**; module 4 (M4)** was characterized by spatial features of knee flexors (SEM, BFM) and temporal features for late swing phase. The peak timing of temporal motor module features was shown in **Table 4**.

Table 4: The activation peak timing of temporal motor modules in the participant during the curvilinear gait

Modules	M1	M2	M3	M4
OCG	21	61	82	63
ICG	8	66	86	66

Note: Values are presented as the percentage (%) of total gait phase. OCG: Paretic leg located at outside of the curve during curvilinear gait; ICG: Paretic leg located at inside of the curve during curvilinear gait

4.3. Quality of data reconstruction of four motor modules

As shown in **Table 5**, VAFs of four motor modules extracted from the paretic leg were both more than 90 during OCG and ICG. Therefore, results of motor module extraction were estimated to be reliable.

Table 5: Variance of accounted for (VAF) of four motor modules during the curvilinear gait

Type of gait	OCG	ICG
VAF	92.42	92.711

Note: OCG: Paretic leg located at outside of the curve during curvilinear gait; ICG: Paretic leg located at inside of the curve during curvilinear gait

5. Discussion

Generally, compared with the rectilinear gait (RG), the curvilinear gait (CG) is more challengeable in terms of the risk of falling because of the requirement of unpredictable and additional motor control for changing gait direction together with forward gait propulsion. Although there have been vigorous studies on RG-related motor modules, few investigations so far on motor module regarding CG especially for patients with neurological disorder have conducted. Therefore, this study was conducted to identify spatial and temporal features of CG-related motor modules from the paretic leg of stroke patients during OCG and ICG. Moreover, by comparing the results of this study with ones of a previous study that reported recently CG-related motor modules for the healthy, this study was aimed to discuss clinical significances for future gait rehabilitation

First, from spatial motor module perspective, as for the comparison between motor modules of the patient in this study and modules of the healthy reported by a previous study (Bejarano et al., 2017), the results of this study generally showed considerable similarity with the ones of a previous study. However, subtle differences were found in each motor module.

For module 1, the patient of this study had the decreased weighting of RFM, VMM and GLU during the early stance phase of OCG when compared with the healthy of a previous study (Bejarano et al., 2017). It implied a clinical significance that the patient with hemiparesis had a difficulty of weight acceptance. Whereas, during ICG, the distinct decreased weighting of RFM and VMM was also observed. For module 2, even though it was similar that the weighting of GCM in the patient was characterized during both OCG and ICG when compared with the healthy, the excessive increase of SEM in the patient was observed during OCG when compared with the healthy. It implied a clinical significance that the patient with hemiparesis tried to compensate the weakness of GCM by SEM during the mid-late stance phase. For module 3, the patient of this study showed the excessive increased weighting of VMM during the early stance phase of both OCG and ICG when compared with the healthy. It implied a clinical significance that the patient had a spastic synergistic pattern which is simultaneous activation of hip flexor and knee extensor during swing phase of gait (Finley, Perreault, & Dhaher, 2008). Lastly, for module 4, the excessive decreased of SEM and BFM during the late swing phase of OCG and ICG respectively, were found in the patient of this study when compared with the health of previous study. It implied a clinical significance that patient had a difficulty with deceleration of the knee extension for preparation of the stance phase.

Second, from temporal motor module perspective, the most apparent difference that the patient of this study was shown a rough time-varying activation of each motor module when compared with the health of a previous study. In particular, the peak timing of module 2 showed a distinct delay during both OCG and ICG. Previous studies have been reported a significance of the delayed activation peak timing of temporal motor module, especially related to M2, that would be associated with decrease in gait speed (Routson, Clark, Bowden, Kautz, & Neptune, 2013). Lastly, in this study, VAFs of motor modules were high (> 90) during both OCG and ICG. It implied that the quality of the extracted motor modules was high and reliable. However, this study had an obvious limitation to interpret the results in terms of generalization because of study design that observed a single case of patient with hemiparesis. Furthermore, it was not possible to compare the results in this study numerically with the ones in a previous study because methodology to extract motor modules was subtly different. However, this study would provide a clue of abnormal motor modules which controlled CG in patient with hemiparesis. Therefore, additional experiments will be necessary to ensure the clinical significance discussed in this study.

6. Conclusion

Through this single-case study, in conclusion, abnormal spatial and temporal feature of each motor module during the curvilinear gait in a stroke patient was observed and its clinical significance was discussed. Therefore, future gait rehabilitation for the stroke patient will need to consider tailored approaches based on the deterioration of motor modules during the gait.

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