Gait & Posture 62 (2018) 378–383

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Full length article

Regulation of quasi-joint stiffness by combination of activation of ankle muscles in midstances during gait in patients with hemiparesis

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ARTICLE INFO

Keywords:
Stroke
Ankle
Stiffness
Coactivation
Gait

ABSTRACT

Background: The regulation of ankle joint stiffness by combination of activation of plantarflexor and dorsiflexor during gait has not been investigated in patients with hemiparesis. The objective of the present study was to examine the relationship between combination of activation of ankle muscles and quasi-joint stiffness (QJS) during the stance phase of gait.

Methods: The activation of the medial head of the gastrocnemius (MG), soleus, and tibialis anterior, gait parameters were collected from 19 patients with hemiparesis due to stroke and from 12 healthy controls using a three-dimensional motion analysis system. The indexes of reciprocal activation and coactivation were calculated from the ratio of plantarflexor to dorsiflexor activation and magnitude of coactivation (MC), which is computed by multiplying an index of simultaneous activation of ankle muscles by plantarflexor activation.

Results: QJS was significantly correlated with MC of MG on the paretic side, whereas it correlated with the ratio of MG ($r = 0.63$, $p < 0.05$) in healthy controls and the ratio of MG ($r = 0.67$, $p < 0.05$) and soleus ($r = 0.61$, $p < 0.05$) on the non-paretic side in midstance. Furthermore, QJS on the paretic side was lower than that on the non-paretic side and in healthy controls ($p < 0.05$).

Significance: Our findings support that the regulation of QJS in midstance by reciprocal activation is altered on the paretic side, whereas it may be regulated by reciprocal activation and enhanced by relatively high activity of plantarflexor on the non-paretic side and in healthy controls.

1. Introduction

Ankle joint stiffness, which is called quasi-joint stiffness (QJS) during gait, is a key factor for a walking performance in patients with hemiparesis. Joint stiffness contributes to generation of power at a joint by energy storage and release mechanism [1]. Our previous study showed that QJS during gait was significantly related to maximum ankle joint power at push off on the paretic side in patients with hemiparesis, which generates propulsion [2]. Furthermore, there was a significant positive correlation between the QJS on the paretic side and gait speed in patients with hemiparesis [2].

Joint stiffness during gait is regulated by variations in the forces produced by the simultaneous activation of both agonist and antagonist muscles, which means coactivation [3]. Leg stiffness which is directly related to ankle joint stiffness was increased by coactivation during stabilization actions in healthy controls [4,5]. Several studies found that coactivation at the ankle joint in patients with central nervous system disorder, such as stroke, increased during gait [6,7]. Kitatani demonstrated that the compensation for decreased plantarflexor strength and moment on the paretic side during gait led to greater coactivation in patients with hemiparesis [7,8]. Moreover, a previous study suggested that excessive coactivation may increase QJS in midstance and provide stability on the paretic side during gait [7]. However, our previous study reported that QJS in midstance on the paretic side was lower than those on the non-paretic side and in healthy controls [9]. Previous studies examined the relationship between ankle coactivation and temporal parameter, gait speed, kinematics and kinetic parameters, and clinical factors in patients with hemiparesis, but not QJS [7,8,10]. Therefore, conflicts indicated that the relationship between coactivation and QJS in midstance on the paretic side during gait in patients with hemiparesis has not been clarified.

In stance phase during gait in healthy controls, reciprocal activities of plantarflexor and dorsiflexor were regulated at the level of the cortex and spinal cord [11,12]. Reciprocal activity means simultaneous activity of muscles with a mechanical action on a joint (agonist) and inhibition of muscles with the opposite mechanical action (antagonists)

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https://doi.org/10.1016/j.gaitpost.2018.03.042
Received 18 September 2017; Received in revised form 13 February 2018; Accepted 24 March 2018

[13]. In midstance during gait in healthy controls, the activity of tibial anterior muscle decreased and that of plantarflexors increased to control the forward tilt of the lower leg [14]. Falconar and Winter suggested that the net joint moment is the algebraic sum of moments generated by individual activities of agonist and antagonist muscles [3]. QJS on the non-paretic side in patients with hemiparesis and healthy controls was not regulated by the activity of a single muscle in plantarflexors and dorsiflexor in midstance during gait in our previous study [9]. Therefore, QJS in midstance in healthy controls may be related to the reciprocal activation of ankle muscles but not coactivation. On the other hand, QJS in midstance on the paretic side may be related to coactivation, considering the increased coactivation in midstance on the paretic side and the significant correlation between coactivation and kinetic data at ankle joint on the paretic side in patients with hemiparesis in previous studies [7,8]. The difference between the regulation of QJS by coactivation and reciprocal activation would have an effect on the value of QJS because of the difference in relatively increased antagonist (dorsiflexor) activation. However, no report is available on the relationship between QJS and combination of activation of ankle muscles during gait in patients with hemiparesis and healthy controls.

The objective of our study was to determine whether QJS at the ankle in the midstance of gait is related to the reciprocal activation and coactivation of the plantarflexor and dorsiflexor muscles in patients with hemiparesis and in healthy controls

Understanding the relationships between coactivation and reciprocal activation and QJS on the paretic side may be useful for gait training development in patients with hemiparesis.

2. Materials and Methods

2.1. Participants

A total of 19 patients (11 males and 8 females) with hemiparesis due to stroke and 12 controls (6 males and 6 females) of comparable age and anthropometric characteristics were included in the present study (Table 1). The inclusion criteria for subjects with hemiparesis due to stroke were (1) unilateral cerebral lesions that did not involve brainstem or cerebellar lesions, confirmed by computed tomography or magnetic resonance imaging, (2) the ability to walk at least 7 m without assistive devices, (3) the ability to follow verbal commands, (4) a foot tap score < 5, as defined by Chino [15], (5) a gait speed < 80 cm/sec, and (6) a post-stroke duration of at least one month. The inclusion criteria for controls included criteria 2 and 3 and not having a neurological lesion. Subjects with hemiparesis and controls were excluded if they had (1) unstable medical conditions, (2) previous leg fracture, major orthopedic surgery, or an actual orthopedic condition interfering with locomotion, (4) abnormal mental status, and (5) higher brain dysfunction, which skewed the measurements. All participants gave written informed consent before data collection, and the study was approved by the institutional review board.

2.2. Gait assessment

The subjects walked for 3–10 trials along the 7-m walkway at a self-selected comfortable pace without assistive devices. Ten reflective markers were placed on seven segments according to the anatomical positions suggested by Data Interface File Format (DIFF) [16]. Two-dimensional kinematics were collected with three-dimensional motion analysis capture with an 8-camera motion analysis system (120 Hz) (MAC 3D, Motion Analysis Corporation, Santa Rosa, CA, USA). Ground reaction force data were acquired at a 1,200-Hz sampling rate using four 90 × 60-cm force plates (Anima Corporation, Chofu, Tokyo, Japan). Mean values of 5–10 trial data for each subject were used for analysis. The kinematic and kinetic data of the ankle joint in the sagittal plane on the paretic side and non-paretic side of patients and on the right side of the controls were calculated using the KineAnalyzer (Kissei Comtec Corporation, Matsumoto, Nagano, Japan). The kinematic and kinetic data were filtered using low-pass FIR filter, with a cutoff frequency of 10 and 20 Hz, respectively. Moreover, KineAnalyzer was used to calculate gait speed and spatiotemporal parameters.

The QJS from the slope of the linear regression of the ankle joint moment versus the ankle angle during the second rocker interval divided into early and midstances was calculated according to the previous study [9] (Fig. 1). Early and middle stances in the second rocker interval are defined as the intervals from the maximum plantarflexion angle in stance of a leading leg to toe off of a trailing leg and from toe off of a trailing leg to maximum dorsiflexion angle in stance of a leading leg, respectively.

Table 1
Characteristics of the subjects[a].

	Hemiparesis n = 19	Control n = 12
Sex	11 M/8F	6 M/6F
Age (years)	54.6 (SD 9.8)	55.1 (SD 13.3)
Height (m)	163.7 (SD 6.5)	161.0 (SD 9.5)
Weight (kg)	59.5 (SD 9.8)	58 .0 (SD 10.9)
Diagnosis	Cerebral hemorrhage 13 Cerebral infarction 6	
Paretic side	10R/9L	
Time post-stroke (Month)	25.4 (SD 33.1)	
SIAS[b]		
Total scores	51.9 (SD 8.3)	
Foot tap	2.8 (SD 1.4)	
QMR[c]	2.4 (SD 0.7)	
Ankle DF ROM[d]	3.4 (SD 4.7)	

[a] Subject characteristics, group means, and standard deviations.

[b] SIAS assesses Neurologic impairments (upper- and lower-limb motor function, muscle tone, sensory function, range of motion, deep tendon reflexes, pain, trunk function, visuospatial function, speech). There are 22 items, and each item is rated from 0 (severely impaired) to 3 (normal) for muscle tone, sensory function, range of motion, pain, trunk, higher cortical function, and unaffected side function or to 5 (normal) for motor function. The total score is 76. The content of foot tap test is repeated plantar-dorsi flexion at three times with sitting or supine positions.

[c] Muscle tone in the ankle plantar flexors was evaluated using the quality of muscle reaction (QMR) in the modified Tardieu scale (MTS) at 0° of knee extension in the supine position. The QMR grades muscle tone on a scale of 0–4 at the fastest stretching velocity.

[d] The range of ankle dorsiflexion was measured with a goniometer in increments of 5°.

2.3. Electromyographic assessment

Electromyography (EMG) electrodes with amplifier (NM-512, Nihon Kohden Corporation, Shinjuku, Tokyo, Japan) were attached to the muscle bellies of the tibialis anterior, medial gastrocnemius (MG), and soleus muscles. Electrode placement was performed based on the SENIAM recommendations [17]. EMG signals were transferred to the multi-telemeter system (WEB-5500, Nihon Kohden Corporation, Shinjuku, Tokyo, Japan) at a sampling rate of 1,200 Hz. Furthermore, the EMG signals were analyzed using the KineAnalyzer (Kissei Comtec Corporation, Matsumoto, Nagano, Japan) and were band pass filtered (30–500 Hz), full-wave rectified, and time normalized to the mean cycle duration set at 100% (Fig. 1). The non-low-pass EMG signal data were averaged at 5–10 strides in each subject. The average EMG amplitude of each muscle during the second rocker in the early and middle stances was normalized by the averaged EMG amplitude of that over the entire gait cycle [18]. The magnitude of coactivation (MC) was calculated as follows [19]: