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Relationship between activation of ankle muscles and quasi-joint stiffness in early and middle stances during gait in patients with hemiparesis

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ABSTRACT

It is unclear whether muscle contraction is necessary to increase quasi-joint stiffness (QJS) of the ankle joint during gait in patients with hemiparesis. The purpose of the present study was to investigate the relationship between QJS and muscle activation at the ankle joint in the stance phase during gait in patients with hemiparesis. Spatiotemporal and kinetic gait parameters and activation of the medial head of the gastrocnemius (MG), soleus (SOL), and tibialis anterior (TA) muscles were measured using a 3-dimensional motion analysis system and surface electromyography, in 21 patients with hemiparesis due to stroke and 10 healthy individuals. In the early stance, the QJS on the paretic side (PS) of patients was greater than that on the non-PS ($p < 0.05$) and not significantly correlated with activation of the three muscles. In the middle stance, the QJS on the PS was lower than that on the non-PS ($p < 0.05$) and that on the right side of controls ($p < 0.001$), which was positively correlated with activation of the MG ($r = 0.51$, $p < 0.05$) and SOL ($r = 0.49$, $p < 0.05$). In the patients with hemiparesis, plantarflexor activation may not contribute to QJS in the early stance. On the other hand, QJS in the middle stance may be attributed to activation of the MG and SOL. Our findings suggest that activation of the MG and SOL in the middle stance on the PS may require to be enhanced to increase QJS during gait in patients with hemiparesis.

1. Introduction

Joint stiffness is an important factor for walking in patients with hemiparesis. Previous studies have suggested that an increase in joint stiffness could lead to a decrease in ground contact time, which contributes to a greater return of the elastic energy stored during the contact phase [1]. Similarly, in the patients with hemiparesis, an increase in the stiffness at the ankle joint on the paretic side (PS) would contribute to the generation of plantar-flexion moment by an energy storage and release mechanism [2,3]. In fact, during walking in patients with hemiparesis, ankle stiffness, which is referred to as quasi-joint stiffness (QJS), is negatively correlated with stance time and positively correlated with maximum ankle power at push-off [4].

QJS involves active (AC) and passive components (PC). The AC is the voluntary and stretch-reflex-mediated contraction of the muscle [5]. Paresis and overactivity, which are common signs in patients with hemiparesis, affect the AC of QJS in the stance phase of walking. A previous study reported that co-activation of ankle dorsiflexor and plantarflexor muscles on stance during walking was decreased on the affected side because of paresis [6]. On the other hand, it was also demonstrated that spasticity increased the stretch reflex on the PS during walking and caused overactivity of the medial gastrocnemius (MG) [7]. The PC includes viscoelastic properties of all structures located within and over the joint [8]. Contracture following disuse due to hemiparesis is an abnormal change in the PC of the QJS. Plantar flexor contracture in patients with hemiparesis leads to higher passive stiffness at the ankle joint on the PS as compared with controls [3].

Lamontagne et al. [3] reported that the AC on the PS contributed to QJS during walking by 73.2%. However, the effect of the AC of QJS during walking in patients with hemiparesis has not been elucidated. In a previous study, decrease of QJS on the PS during gait after intrathecal injection of baclofen (ITB) improved gait speed in patients with hemiparesis [9]. Horn et al. [10] reported that in 5 of 28 patients with brain injury, after ITB administration, the gait speed worsened, and seven patients showed no change in gait speed. This inconsistency may lead to confusion in clinical decision-making because the relative contributions of paresis and overactivity to QJS during walking have not been distinguished

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clearly [11]. To our knowledge, there is no study separately evaluating the effects of paresis and spasticity on the AC of QJS during walking in patients with hemiparesis. Lamontagne et al. [7] suggested that there may be a combination of high activation of the plantarflexors due to spasticity and low activation of the plantarflexors due to paresis. Spasticity can affect the AC in the early phase of stance when the lengthening velocity of the plantarflexor muscles is high. On the other hand, paresis can affect the AC in the late phase of stance when the lengthening velocity of the muscles is low. Therefore, analysis of QJS and muscle activation by subdividing the stance phase during walking might enable evaluation of the relative contribution of paresis and spasticity to the AC. In a recent study, the second rocker interval was subdivided into early (ES) and middle stances (MS) [9]. Clarifying QJS and the AC in the subdivided stance phases in patients with hemiparesis may be helpful in determining which weakness, i.e., paresis or spasticity, should be treated. The purpose of the present study was to investigate the relationship between QJS and muscle activation of the plantarflexors and dorsiflexors in each subdivided stance phase in patients with hemiparesis. It was hypothesized that QJS in patients with hemiparesis increased in the ES and decreased in the MS and that QJS is positively correlated with activation of the plantarflexors in the ES and negatively correlated with activation of the plantarflexors in the MS.

2. Materials and methods

2.1. Participants

Twenty-one patients (12 males and 9 females) with hemiparesis due to stroke (age range, 30–72 years) and ten controls (4 males and 6 females) of comparable age (age range, 31–78 years) and anthropometric characteristics participated in the present study (Table 1). The inclusion criteria for subjects with hemiparesis due to stroke were as follows: (1) unilateral cerebral lesions confirmed by computed tomography or magnetic resonance imaging; (2) the ability to walk at least 7 m without assistive devices; and (3) the ability to follow verbal commands. The inclusion criteria for controls included (2) and (3). Subjects with hemiparesis and controls were excluded if they had the following: (1) abnormal circulatory and respiratory status; (2) a history of orthopedic problems; (3) brainstem or cerebellar lesions; (4) abnormal mental status; and (5) higher brain dysfunction, which skewed measurements.

In patients with hemiplegia, ankle motor function was assessed using foot-tap, graded on a scale of 0–5, according to the stroke impairment assessment set [12]. Muscle tone in the plantarflexors was evaluated using the quality of muscle reaction (QMR), in the modified Tardieu scale (MTS), at 0° knee extension in the supine position [13]. The QMR grades muscle tone on a scale of 0–4 at the fastest stretching velocity. These tests were performed using standardized protocols by an experienced physical therapist (Y. S.). All participants gave written informed consent before data collection, and the study was approved by the institutional review board.

Table 1
Characteristics of subjects with hemiparesis and control.

	Hemiparesis	Control
N	21	10
Gender	12M/9F	4M/6F
Age (years)	56.2 (SD 10.5)	53.8 (SD 13.7)
Height (m)	162.7 (SD 7.8)	159.6 (SD 9.7)
Weight (kg)	59.4 (SD 10.4)	56.8 (SD 11.5)
Diagnosis	Cerebral hemorrhage 14 Cerebral infarction 7	
Paretic side	11R/10L	
Time since neurologic event (month)	29.4 (SD 37.1)	
SIAS		
Total scores	52.6 (SD 6.42)	
Foot tap	3.10 (SD 1.22)	
QMR	2.19 (SD 0.68)	
Ankle DF ROM	4.28 (SD 4.82)	

Subject characteristics, group means, and standard deviations, 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. 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. The range of ankle dorsiflexion was measured with a goniometer in increments of 5°.

2.2. Gait assessment

All subjects were examined with three-dimensional motion analysis captured with an 8-camera motion analysis system (120-Hz) (MAC 3D, Motion Analysis Corporation, Santa Rosa, CA, USA). Ten reflective markers were placed with adhesive tape on 7 segments according to the anatomical positions suggested by Data Interface File Format (DIFF) [14]. Ground reaction force data were acquired at a 1200-Hz sampling rate using four 90 cm × 60 cm force plates (Anima Corporation, Choufu, Tokyo, Japan). The subjects walked along the 7-m walkway at a self-selected comfortable pace without assistive devices. Mean value of 5–10 stride data for each subject was used for analysis. The position data of markers and ground reaction forces were processed using the KineAnalyzer (Kissei Comtec Corporation, Matsumoto, Nagano, Japan), to calculate the kinematic and kinetic data of the ankle joint in the sagittal plane on the PS and non-PS of patients and on the right side (RS) of the controls. The kinematic and kinetic data were filtered using low-pass FIR filter, with a cut-off frequency of 10 Hz and 20 Hz, respectively. KineAnalyzer was used to calculate gait speed and spatiotemporal parameters.

We calculated QJS from the slope of the linear regression of the ankle joint moment versus the ankle angle during the second rocker interval, subdivided into the ES and MS, according to the previous studies [9,15] (Fig. 1).

2.3. Electromyographic assessment

Electromyography (EMG) measurements were performed at 1200 Hz with the multi telemeter system (WEB-5500, Nihon Kohden Corporation, Shinjuku, Tokyo, Japan). Ten-mm EMG electrodes with amplifier (NM-512, Nihon Kohden Corporation, Shinjuku, Tokyo, Japan) were placed over the muscle bellies of the tibialis anterior (TA), medial gastrocnemius (MG), and soleus (SOL) muscles. 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 to 100%. The non-low-pass EMG signal data were averaged at 5–10 strides in each subject. The average amplitude of each muscle during second rocker in the ES and MS was normalized to the averaged amplitude of that during one gait cycle [16].

2.4. Statistical analysis

Gait speed, cadence, and gait step time were compared between patients with hemiparesis and controls using unpaired *t*-tests.