Muscle Tension Analysis in Stroke Patient Sit-to-Stand Motion by Joint Torque-Based Normalization

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***Abstract*— Patients with stroke exhibit distinct muscle activation features in sit-to-stand motion due to motor deficiency. Muscle activation amplitude is an important feature but has not been clarified due to the lack of a valid normalization method to enable intra-subject comparisons. This study, focusing on the paretic side, examines the change in muscle tension manifested in activation amplitude for a patient with stroke in serial measurements by a novel method based on joint torques. We constructed a musculoskeletal model, calculated joint torques by inverse dynamics, and solved muscle activation by forward dynamics simulation. Results showed that tibialis anterior, gastrocnemius, vastus lateralis, rectus abdominis, and erector spinae muscles on the paretic side showed significant improvement in generating maximum muscle tension after a rehabilitation training for 120 days.**

I. INTRODUCTION

The global population is aging rapidly, accompanied by a steep increase in the prevalence of stroke disease [1]. Today, stroke is a leading cause of disability and death. Patients with stroke suffer motor deficiency in sit-to-stand (STS) motion. For instance, they are prone to falling, which is a common cause of hospitalization [2]. STS is thus a rehabilitation focus for training to improve stroke patients' independence and life qualities. To facilitate diagnoses and develop effective rehabilitation strategies, it is essential to understand the mechanism in STS in which patients suffer substantially.

Patients suffering stroke show distinct muscle activation temporal features in STS [2]. Besides muscle activation time, activation amplitude is also an important feature for interpreting the contribution of muscle strength in motions and evaluating motor performance [3]. However, activation amplitude features, especially amplitude changes in rehabilitation, remain unclear due to the lack of a feasible normalization method for stroke subjects.

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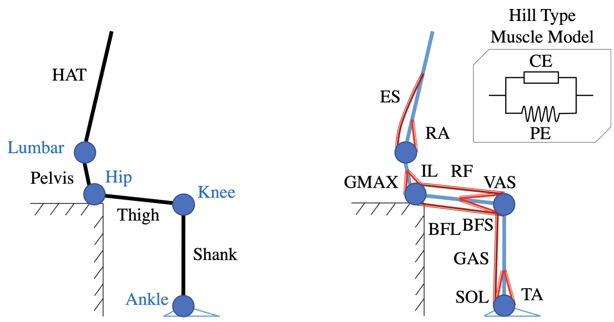

(a) Skeletal Model (b) Muscle Model

Fig. 1. Musculoskeletal model. (a) Skeletal model for joint torques calculation by inverse dynamics. (b) Hill Type muscle model for forward dynamics simulation.

Both muscle activation time and amplitude measured by surface electromyography (sEMG) on different days during rehabilitation may differ. sEMG normalization is necessary for comparing activation amplitudes due to different human skin conditions and slight inconsistencies in manual placements of sEMG sensors on different days, even if it is with the same subject. If changes in activation amplitude could be clarified for patients in stroke rehabilitation, it would unveil how patients' muscle tension improvements reflect motor recovery, thus suggesting effective training strategies. Therefore, this study, first focused on the paretic side, aims to clarify muscle tension improvements manifested in muscle activation amplitude increases in stroke rehabilitation by normalizing muscle activation based on joint torques, considering that activated muscle forces generate joint torques. Both muscle activities and joint torques were thus examined in this study.

II. METHODS

A. Musculoskeletal Model

A skeletal model with segments of shank, thigh, pelvis, and HAT (head, arm, and trunk) is constructed to calculate joint torque $\mathbf{T}_{\mathrm{jnt}}$ at the ankle, knee, hip, and lumbar joints from body kinematics [4], as in Fig. 1 (a). $\mathbf{T}_{\mathrm{jnt}}$ is solved given joint angles, segment inertia, viscous resistance forces, gravitational forces, and non-linear forces, by inverse dynamics.

A muscle model in Fig. 1 (b) is constructed for forward dynamics simulation to map joint torque τ_k at the ankle, knee, hip, and lumbar joints to motion [4]. Eleven muscles are considered: tibialis anterior (TA), soleus (SOL), gastrocnemius (GAS), rectus femoris (RF), vastus lateralis (VAS), biceps femoris long head (BFL), biceps femoris short head (BFS), gluteus maximus (GMAX), rectus abdominis (RA), erector spinae (ES), and iliopsoas (IL). τ_k is generated by muscle forces F_i exerted at muscle moment arms r_{ki}, as in (1). Hill Type muscle model is applied to calculate F_i, which equals the sum of actively generated tension F_i^{CE} by the contractile element (CE) and passively generated tension by the parallel element (PE) [5]. F_i^{CE} is calculated from (2), where f_{fl} and f_{fv} indicate muscle force-length and force-velocity relationships, respectively; $F_i^{\max}$ is maximum muscle contraction force; $\hat{m}_i$ is the normalized muscle activation amplitude. The passively generated tension presents when a muscle extends beyond its optimal length.

Due to muscle redundancy induced by bi-articular muscles, the normalized muscle activation amplitude $\hat{m}_i$ in (2) is solved by optimization. Under the constraint that τ_k in (1) equals $\mathbf{T}_{\mathrm{jnt}}$ obtained from body kinematics, $\mathbf{T}_{\mathrm{jnt}}$ is thereupon decomposed to the desired muscle activation $\hat{m}_i$ by minimizing the error between simulated $\hat{m}_i$ and measured muscle activation m_i, as in (3), to let the model generate a motion resembling the motion performed.

$$\tau_k = \sum_{k=1}^{4}\sum_{i=1}^{11} r_{ki}F_i, \tag{1}$$

$$F_i^{\mathrm{CE}} = f_{\mathrm{fl}} f_{\mathrm{fv}} F_i^{\max}\hat{m}_i, \tag{2}$$

$$\mathrm{Z} = \sum_{i=1}^{11}\frac{1}{2}||\hat{m}_i - m_i||^2. \tag{3}$$

B. Measurement Experiment

Measurement experiments were conducted with one patient with stroke for serial assessments of motor recovery using the proposed models. The participant is male, 54 years old, and sustains motor impairment on his left side due to putaminal hemorrhage, with a total rehabilitation time of 120 days. Four measurements (on day 25, 95, 116, 144 after stroke onset) were done when the patient was receiving rehabilitation training in the hospital. The patient was invited to repeat 10 trials of sit-to-stand without external assistance at a self-paced speed.

Body kinematics, feet and hip reaction forces, and muscle activities were recorded at 100 Hz, 2,000 Hz, and 2,000 Hz, respectively, using optical motion capture system (Motion Analysis Corp.), force plates (TechGihan Corp.), and Wireless sEMG sensors (Cometa Corp.). sEMG sensors were placed at the same muscles considered in the musculoskeletal model (in Fig. 1 (b)), except for iliopsoas (IL) since IL is an inner hip joint flexion muscle that cannot be measured with sEMG. Each muscle is either uniarticular or bi-articular and contributes to STS by flexing or extending the ankle, knee, hip, and lumbar joints. Measured muscle activation (m_i) signals were band-pass filtered with a zero-lag fourth-order Butterworth filter of 40–400 Hz and rectified with a fourth-order low-pass Butterworth filter at 4 Hz. The reaction force data was low-pass filtered at 20 Hz. Each STS trial, consisting of 1 second before and 2 seconds after the seat-off moment, was extracted from the whole process for data synchronization.

Informed consent was obtained from the patient. Experiments were approved by the Morinomiya Hospital, Japan.

III. Results and Discussion

Maximum muscle tension and peak joint torque generation of the paretic side between the first (day 25) and last (day 144) measurements were examined by paired t-tests [6]. The patient's TA, GAS, VAS, RA, and ES muscles showed significant increases ($P < 0.05$) in maximum muscle tension and activation amplitude. Since stroke patients with no or low-amplitude activation in their TA muscles were prone to falling [2], the significant increases in activating the TA muscle may explain why our patient became less likely to fall as he recovered. Additionally, significant increases in maximum joint torque generation were found at the knee and lumbar joints, whereas the hip joint showed a significant decrease in torque generation. It may suggest that the patient relied less on the hip joint and adopted a different strategy in activating muscles associated with the hip joint to stand up as motor abilities recovered.

IV. Conclusion

This study compared and clarified muscle tension improvements reflected in motor recovery of the paretic side for a patient in serial measurements during stroke rehabilitation, using the proposed joint torque-based normalization method. Our results may assist in suggesting effective rehabilitation strategies for stroke survivors. For future work, we aim to explore a better optimization algorithm to minimize errors and consider more stroke and healthy subjects to better understand patients' motor recovery processes.

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