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Analysis of Finger Muscular Forces using a Wearable Hand Exoskeleton System

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Abstract

In this paper, the finger muscular forces were estimated and analyzed through the application of inverse dynamics-based static optimization, and a hand exoskeleton system was designed to pull the fingers and measure the dynamics of the hand. To solve the static optimization, a muscular model of the hand flexors was derived. The experimental protocol was devised to analyze finger flexors in order to evaluate spasticity of the clenched fingers; muscular forces were estimated while the flexed fingers were extended by the exoskeleton with external loads applied. To measure the finger joint angles, the hand exoskeleton system was designed using four-bar linkage structure and potentiometers. In addition, the external loads to the fingertips were generated by cable driven actuators and simultaneously measured by loadcells which were located at each phalanx. The experiments were performed with a normal person and the muscular forces estimation results were discussed with reference to the physical phenomena.

Keywords: hand rehabilitation, wearable system, bionic exoskeleton, musculoskeletal model, inverse dynamics, static optimization

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1 Introduction

Stroke is one of the critical causes of disability in cognition or movement[1]. Among the disabilities in movement, a loss of hand function is critical for independent activities of daily living, because the hand is a core body part manipulating an object and interacting with environments. Therefore, the demand for hand rehabilitation has been increased, whose aim is to alleviate spasticity of finger muscles and enhance hand functions. The muscle spasticity is the most common symptom in the stroke patients, which is caused by hyperexcitation of stretch reflex, stiffened tissues, and shortened fascicle length[2–6].

To deal with spastic muscles, it is very important to evaluate the level of spasticity to adjust the intensity and frequency of the rehabilitation treatment. In a clinic, a medical doctor usually pulls the fingers with appropriate force to diagnose the muscle spasticity. However, since the evaluation process highly depends on the doctor's skills and experiences, it is difficult to conduct the evaluation in an objective and quantitative manner. To resolve the limitation, various types of wearable devices have been developed to assist the therapists[7–12].

Since the robotic devices are able to measure physical quantities repeatedly and quantitatively, it may be able to improve the evaluation result significantly. For instance, various mechanisms were adopted to measure finger joint angles, such as optical linear encoder, a 3D magnetic position sensor, and an optic fiber sensor[7–9]. The fingertips were pulled by pneumatic muscles to assist the patient's voluntary movement and the forces were measured by pressure sensor[10]. Even though the active research has been conducted on the robotic devices, the previously developed systems are not appropriate for clinical evaluation of the stroke hand, because none of them are able to apply the pulling force to the finger while simultaneously measuring the applied force and its joint kinematics with full range of motion of the finger[11–14]. The reason why such a robotic device

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has rarely been developed is the small space around the fingers.

Therefore, in this study, a novel hand exoskeleton system was developed, which applied pulling force at the fingertips using a cable-driven actuation mechanism, and the joint angles and the applied force were measured by rotary potentiometers and loadcells embedded in the linkage structures. The cable-driven actuation system was designed as a relatively simple mechanism which pulled each fingertip because of the limited space on the finger. In spite of the simple loading condition, the device was able to extend the flexed fingers while measuring the applied force and the joint angles, which allowed analysis of finger movement under loading.

Although it was available to realize the loading conditions and acquire motion information, an approach was necessary to analyze them, since little work has been done to evaluate spasticity of the hand using the robotic devices. In the case of lower extremity, spasticity of the calf muscle, so called the gastrocnemius, was estimated using the ultrasonography and the robotic device which applied joint torques at the ankle and knee joints and measured the torques and joint kinematics[15]. Unlike the hand, such a study was available due to relatively simple functional structures of the muscles in the ankle joint; the one dorsiflexor and the two plantarflexors[16]. However, since the finger has a complex tendon net and it involves multiple muscles including the intrinsic and extrinsic muscles, it was difficult to apply the same strategy[17].

In such a case, the use of a model-based estimation method is an alternative solution. The model-based method relies on computational modeling of body functions to estimate the muscular forces for given motion information[18]. Static muscular forces generated by intrinsic and extrinsic muscles were investigated using a force transducer that measured the external loads applied to the fingers with a predetermined experimental condition for elimination of muscle redundancy[19]. Also, a two-dimensional musculoskeletal model was developed, which used static analysis to calculate muscular forces[20,21]. Further, several models also incorporated inverse dynamics of the finger[22,23]. Finger muscular forces were studied in a fixed posture to determine the finger positions that minimized tendon force while a piano was played[24], and to investigate the effects of finger extensor mechanisms[25]. Additionally, a three-dimensional dynamic model was developed, incorporating flexion and extension of the three joints, adduction and abduction of the metacarpophalangeal (MCP) joint, muscle contraction dynamics, and the passive force of the MCP joint ligament[26].

Although the biomechanical finger models have been well-established, there exist several limitations remained unsolved. In the dynamic analysis of the finger, external load applied to the finger significantly affects the estimated muscular forces. However, it was ignored in previous analysis of three-dimensional index finger movement in the absence of proper equipment which applied forces to the fingers during free movements[26]. In addition, it has been a difficult task analyzing five fingers simultaneously due to limitation of measurement systems. In this study, the muscular forces in the five fingers were estimated by combining the model-based estimation method with the proposed hand exoskeleton system which realized the experimental protocol similar with the clinical evaluation process. The experimental results were analyzed according to the function and anatomy of the hand.

The remainder of this paper is organized as follows. Section **2** briefly describes the model-based estimation method called inverse dynamics-based static optimization, and the estimation model is described in detail. Section **3** introduces the design and functional features of the hand exoskeleton system, and experimental results are discussed in section **4**. Conclusion and future works are provided in section **5**.

2 Inverse dynamics-based static optimization

For estimation of the muscular forces, inverse dynamics-based static optimization has been a representative model-based estimation method well-organized in Ref. [18]. In this study, the estimation method was applied to the fingers with the proper musculoskeletal model defined as shown in Fig. 1. The inverse dynamic equation was derived to calculate joint torques from the joint kinematics and the external forces measured by the hand exoskeleton. To determine the force applied by a single muscle, the muscular force sharing problem, so called static optimization, was solved for each instant. The optimization process is necessary because the human body has inherent redundancy with larger number of muscles than the degrees of freedom in the skeletal system[27].