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Design and validation of a novel mechatronic transmission system for a wearable tremor suppression device

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HIGHLIGHTS

- A mono-input-multiple-output mechatronic mechanism for tremor suppression is presented.
- The power transferred from the power source to the output is controlled by a 2 W DC motor.
- A single drive motor can be used to support multiple independent outputs.
- The mechanism was validated using tremor data from patients with Parkinson's disease.
- An average of 12.4% RMS error was achieved on a dynamic tremor suppression test.

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ABSTRACT

Traditional treatments, medication and surgery, for tremor management in Parkinson's disease have shown varying effectiveness carry a risk of significant side effects. Recent research and development of wearable tremor suppression technology have shown a promising third solution for tremor management. This paper presents the design of a novel multi-channel mechatronic splitter (MMS) for use in wearable tremor suppression devices. This mechatronic system allows a single drive motor to support multiple independent outputs. The operation (speed and direction) of the MMS is controlled by a 2 W DC motor. This low power characteristic may provide a promising approach to achieving a prolonged operating life for wearable devices. Furthermore, the size of the MMS can be scaled proportionally according to different applications for optimal performance. This paper describes the design, modeling, implementation and characterization of the MMS. The weight of the MMS prototype is 129 g, the maximum output speed is 120 rpm, and the maximum continuous torque is 0.15 Nm. In addition, recorded tremor motion along with voluntary movement from 7 individuals with Parkinson's disease was used to validate the performance of the MMS. The MMS was controlled to suppress tremor motion while following the voluntary movement of the subject. An average of 12.4% RMS error in voluntary motion tracking was achieved on a dynamic tremor suppression test.

1. Introduction

Tremor, the most common movement disorder, is described as an unintentional, rhythmic, oscillatory movement with a particular amplitude and frequency [1,2]. Its manifestation is primarily generated by the stimulations of reciprocally innervated muscles [3]. Clinically, tremors are categorized as resting tremor and action tremor [4]. Resting tremor is often associated with Parkinson's disease (PD) and drug-induced Parkinsonism. Action tremor, which is further divided into postural tremor, isometric tremor and kinetic tremor, is commonly associated with PD, cerebellar lesions, essential tremor, enhanced physiological tremor, metabolic disturbance, and drug or alcohol withdrawal. The reported frequencies of tremors are typically in the range of 3–12 Hz [3,5]. Some recent studies have shown that Parkinsonian tremor and essential tremor incorporate multiple harmonics with frequencies that range from 3.5 Hz to 17.3 Hz [6,7]. This high-frequency tremorous movement significantly affects the activities of daily life for patients and may cause social embarrassment leading to avoidance of social activities.

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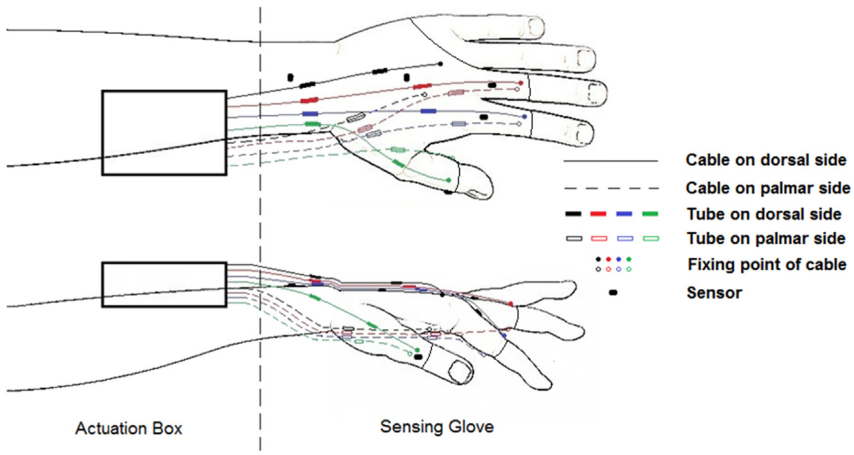

Fig. 1. Schematic of a hand tremor suppression glove. The dashed line separates the actuation box section and the sensing glove section. The actuation box controls the motion of the joint of interest through a number of nonstretchable cables. The cables are located on both sides of the hand. The ones on the dorsal side control the extension of the joint, and the ones on the palmar side control the flexion of the joint. Sensors embedded in the glove provide position information for each joint.

Tremor is often treated with medication. However, the efficacy of medication is unfortunately low, and carries significant side effects [8,9]. In addition to medication, many researchers have investigated the effects of surgical interventions on tremor, including deep brain stimulation (DBS) and stereotactic thalamotomy [10,11]. These procedures may ease certain tremors, but they carry a potential risk of permanent complications, paresthesia, dysarthria, speech impediments and even stroke and hemiparesis [12,13].

Given the complications and adverse effects of the traditional treatments, a less invasive approach with fewer side effects is needed. Rosen, et al., have demonstrated experimentally that people with pathological tremor are unable to accomplish the activities of daily living (ADL) because the magnitudes of the tremors approach the magnitudes of the ADL [14]. The development of mechanical tremor suppression orthoses was proposed as a possible solution to this problem.

Several research groups have developed tremor suppression devices for wrist and elbow tremors [15–26]. An actuator with a controllable viscous rate was designed by Loureiro, et al. [15]. This actuator employed magnetorheological fluids (MRF), the viscosity of which can be controlled in the presence of a magnetic field. The controllability of the MRF is the main advantage over other similar designs [16,17]. However, it is not possible to suppress tremor without impeding voluntary motion using this type of passive actuator. Also, the suppression power of this device is relatively low due to the limited strength of the actuator. Another application of MRF in tremor suppression was investigated by Case, et al. [18]. This actuator was designed using a damper configuration. The performance of the actuator was greatly improved, but the issue of suppressing both voluntary and tremorous motion was not solved.

Although passive technology is safer when applied to orthoses, active technology can achieve better performance. A recent study has shown the success of using pneumatic actuators for suppressing tremor [19]. The force generated by the actuator is sufficient to suppress tremor to a great extent. The proposed device is compact and efficient. However, as a wearable device, it is not realistic for the user to carry the required air compressor. In addition, the noise from either the cylinder or the air source may cause embarrassment to the user. More importantly, air leak and valve failure of the pneumatic actuator may result in serious injury to the user.

A 3 degree-of-freedom (DOF) Wearable Orthosis for Tremor Assessment and Suppression (WOTAS) was the final product of a five-year European project called Dynamically Responsive Intervention for Tremor Suppression (DRIFT) [20–22]. This device was developed to monitor and suppress tremor with minimal restriction to voluntary movement and employs both active and passive strategies. The study results showed superior performance of the active strategy (up to 90% reduction rate in tremor amplitude) over the passive approach. However, this device is very bulky and cosmetically limited. These disadvantages make it infeasible for constant wear.

A successful demonstration of the application of a pneumatic cylinder for suppressing wrist tremor [19] was extended to elbow tremor [7]. Two more DOF were added to the device to control the flexion–extension of the elbow and pronation–supination of the forearm. The fundamental frequency of the tremor was suppressed to a large degree (96.8–98.8%), but the reduction in the second harmonic was only 52.7%–82%. This may be caused by the slow response of the pneumatic cylinder. Although the reduction in tremor magnitude is good, the issues related to a pneumatic actuator make this device unsuitable as a wearable device.

With most of the aforementioned devices, the tremor reduction rate was the primary goal, with the suitability for patient use often being neglected. This has led to many of the devices being bulky and heavy to use. Furthermore, although finger tremor is often significant, existing devices do not compensate for it.

Under these perspectives, a wearable tremor suppression glove (WTSG) was conceived in order to fill this gap in the area of tremor suppression. The main challenge for the design of a WTSG and its application in patient use is the size and weight of the actuators, as well as battery life. Thus, it is necessary to develop a novel mechatronic transmission system that meets the requirements for hand tremor suppression with a compact configuration and sufficiently lightweight.

2. Mechanical design

2.1. Conceptual model and prototyping

The goal of this work was to design and develop a mechatronic transmission system that can be used in a WTSG. A schematic of the concept of the WTSG is shown in Fig. 1. It consists of a sensing glove and an actuation box. These two sections are connected through nonstretchable cables. The sensing glove contains sensors, tubes that guide the cables and insertion points for all cables to transfer force from the actuation box to the hand. The core component of the actuation box is the mechatronic transmission system.

Within the mechatronic transmission system are several modules each, referred to as a multi-channel mechatronic splitter