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A Non-Invasive, Soft Robotic Wearable Glove to Attenuate Hand Tremors

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ABSTRACT

Hand tremors are a widespread medical condition that decreases a patient's quality of life. Due to uncontrollable hand shaking, patients have difficulty completing essential daily tasks. Many also experience embarrassment and anxiety in social settings, which negatively affects many areas of their lives. Current treatments are often invasive, ineffective, and have unwanted side effects. Some non-invasive solutions excessively limit hand motion, making them ineffective in helping the wearer complete tasks, while others are highly visible and bulky. This paper presents a minimalistic, non-invasive, wearable glove that uses active feedback control and miniature, soft robotic pneumatic actuators to attenuate hand tremors while allowing freedom of movement in other directions. We 3D-modelled the hand and wrist and designed our glove and actuators using Fusion 360. These models were imported into Matlab and Simulink, where we simulated the hand tremor, actuation, and control system using spatial contact forces. To actively reduce the tremor amplitude, we used an accelerometer to detect the onset of tremor motion and create a real-time estimate of the hand's position. This estimate drove a closed-loop PI controller that produced force commands for the pneumatic actuators, which applied a counterforce opposing the direction of hand motion. Based on our simulation results, our active glove control system design successfully reduced the hand tremor amplitude by 75%, from a baseline of ±8.0mm to a significantly improved amplitude of ±2.0mm. These results indicate that our proposed solution could effectively attenuate hand tremors to a level that would increase the wearer's quality of life.

Introduction

Tremors in hand are a common medical condition that affects a person's ability to perform daily tasks and feel comfortable in social settings. These tremors are defined as a rhythmic, involuntary oscillatory movement of a body part (Lora-Millan et al., 2021). Hand tremors often occur in the vertical direction, oscillating up and down by a maximum of about ±1cm. Figure 1a illustrates this motion, and Figure 1b shows a graphical representation of one cycle of the oscillatory tremor motion. Tremors that occur in the hands are often a result of either Essential Tremors (ET) or Parkinson's Disease (PD). ET is the most common pathologic tremor, with 4% of adults age 40 and over living with this condition and 95% of them experiencing tremors in the upper limbs (Elble, 2013; Louis, 2009). PD is the second most common neurodegenerative disease, as over one million Americans currently live with the disease, and 60,000 new patients are diagnosed with PD each year (Heusinkveld et al., 2018). With both of these conditions, patients either experience rest tremors or intention tremors. Rest tremors are when the patient experiences hand tremors while their hand is at rest by their side. Patients with intention tremors experience hand tremors when attempting to complete a voluntary movement or action with their hand.

Hand tremors are often a result of abnormal communication or brain activity in parts of the brain such as the cerebellum, globus pallidus, and thalamus, which controls muscle activity (Hua et al., 1998a, 1998b). Figure 1c depicts the thalamus and the peripheral nerves that carry the disruptive signals to the tremoring hand. These tremors hinder a person's fine motor skills and therefore prevent them from completing activities of daily living such as eating, drinking, writing, and self-care. As a result, people with hand tremors are often unable to work, which significantly impacts their quality of life (Shalash et al., 2019). Additionally, in a survey of 75 PD patients, tremors in the hands were recorded as the most bothersome symptom of PD. Patients also reported that their hand tremors are a source of significant social anxiety and embarrassment. This harmed their self-image, sense of security, well-being, and personal and social relationships (Heusinkveld et al., 2018).

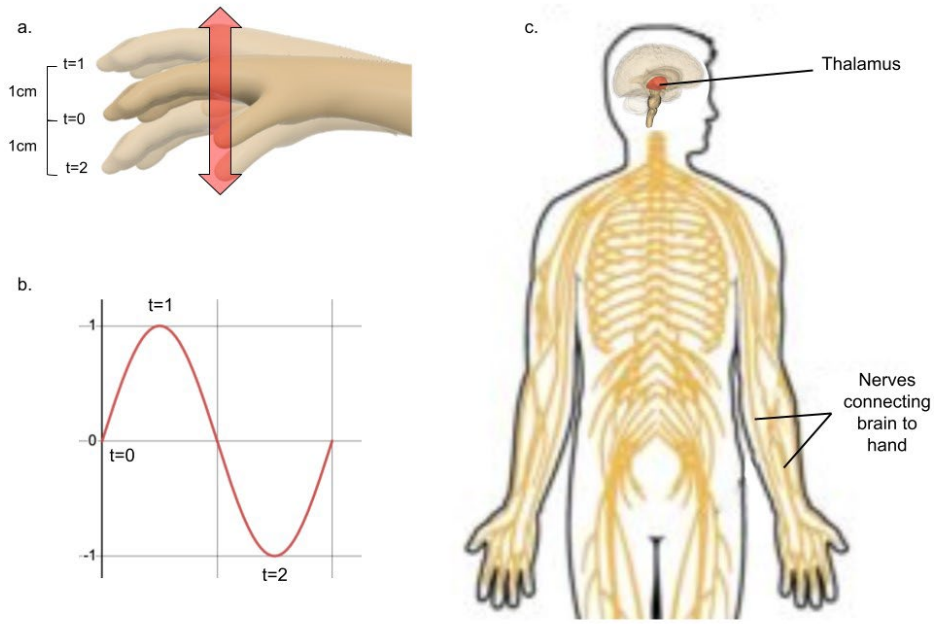

Figure 1: (a) Arrow indicating direction of hand tremor motion with hand position shown at three time intervals. (b) Sine wave graph representing hand tremor motion depicted above in part a. (c) Thalamus in human brain and peripheral nerves connecting brain to hand. Image adapted from "Peripheral Nervous System," n.d.

Current treatments for tremors are categorized as either invasive or non-invasive. Invasive solutions are either pharmaceutical or surgical. Non-invasive treatments include external wearable devices that suppress hand tremors either with electrical stimuli or by preventing oscillatory tremor motion.

Common pharmacotherapy mainly involves propranolol and primidone medications. However, these invasive medications have minimal effectiveness (less than 60% reduction of tremor amplitude), and the majority of patients stop using these medications due to a lack of efficacy or intolerable side effects (Deuschl et al., 2011; Diaz & Louis, 2010). Another common invasive treatment for tremors is deep brain stimulation. This includes direct electrical stimulation of the ventral intermediate nucleus of the thalamus, which disrupts the firing of neurons in the thalamus (Mo & Priefer, 2021). However, deep brain stimulation is expensive, highly invasive, and largely inaccessible to many tremor patients (Kim et al., 2016).

Non-invasive solutions for hand tremors include suppressing tremor motion through electrical stimuli. A wearable device called Cala Trio uses electrical stimuli on wrist nerves that travel to the thalamus in the brain and disrupt pathological tremor oscillations (Mo & Priefer, 2021). However, Cala Trio therapy requires the patient to complete a 40-minute therapy session before they experience relief of tremors. Additionally, side effects often include skin irritation, stinging discomfort, and burns (Isaacson et al., 2020). Similarly, functional electrical stimulation (FES) stimulates motor nerves through electrodes placed on arm muscles. However, inexact placement of the electrodes often leads to ineffective tremor suppression, and many patients using FES experience muscle fatigue, numbness, and a burning sensation in the hand (Bickel et al., 2011; Javidan et al., 1992). As a result, FES cannot be used for long-term relief. Lastly, with both of these solutions, evidence from trials suggests that some patients do not respond to these treatments (Isaacson et al., 2020; Popovifá Maneski et al., 2011).

Non-invasive wearable solutions that limit oscillatory hand motion externally are low-risk, and many are highly effective at suppressing hand tremors. Active orthoses often use motors, pneumatics, or permanent magnet linear motor actuation. These wearable devices use sensors and algorithms to detect tremor motion and actuate specifically based on the data and calculations (Manto et al., 2007; Taheri et al., 2015; Zamanian & Richer, 2017). The efficacy of such devices can range from 77% to 99.8% (Mo & Priefer, 2021).

Semi-active wearable devices often use magnetorheological (MR) fluids, which become more viscous when exposed to a magnetic field. This property can be used to suppress hand tremors by harnessing the resistive force in the MR fluid to suppress tremor motion in the hands (Zahedi et al., 2021). Alternatively, semi-active devices such as a pneumatic handcuff can also use pneumatic actuation to suppress hand tremors (Kalaiarasi & Kumar, 2018).

Lastly, passive wearable devices use mass-spring-damper systems to transfer the vibrational kinetic energy of the hand tremors from the spring to the added mass, which hinders tremor motion. Passive devices do not require a power source (Rudraraju, 2018).

These wearable solutions have the disadvantage of being heavy, bulky, rigid, and highly visible. As a result, they contribute to the social anxiety of hand tremor patients rather than reducing it. Consequently, there is an increasing need for a non-invasive, wearable, minimal, and soft solution to hand tremor suppression. To address this need, we present a soft robotic wearable glove that uses miniature pneumatic actuation to combat tremors in hand. The proposed device is non-invasive and uses soft materials and a concise design to increase comfort and decrease visibility. For our study, we used Matlab and Simulink to simulate tremor motion in hand, measure and calculate information about the motion using an accelerometer and position estimator, control actuation forces with a PI controller, and apply those forces to the hand to simulate and test our device. In addition, we used Simscape Multibody to provide a visual rendering of our simulation.

In the next section, we will discuss the physical design of our soft robotic glove and present our method of detection and actuation. We will also provide details about our Matlab simulation.

Materials and Methods

We chose to use soft robotic materials in our wearable glove to maximize safety and comfort for the user. The pliant, stretchable materials used in soft robotic applications such as our glove allow the glove to fit a wide range of hand sizes comfortably. Additionally, the inherent flexibility of the soft silicon pneumatic actuators enables the wearer to have a wide range of motion while wearing the glove; as a result, they can complete daily tasks without unnecessary limitations. In addition, this property allows for safe interaction between the actuators and the wearer due to the soft robotic silicon actuator's high compatibility with the human body (Rus & Tolley, 2015). The overall design of the glove is meant to be lightweight, minimal in size, comfortable, and facilitative of the wearer's freedom to perform tasks without unwanted hindrance.

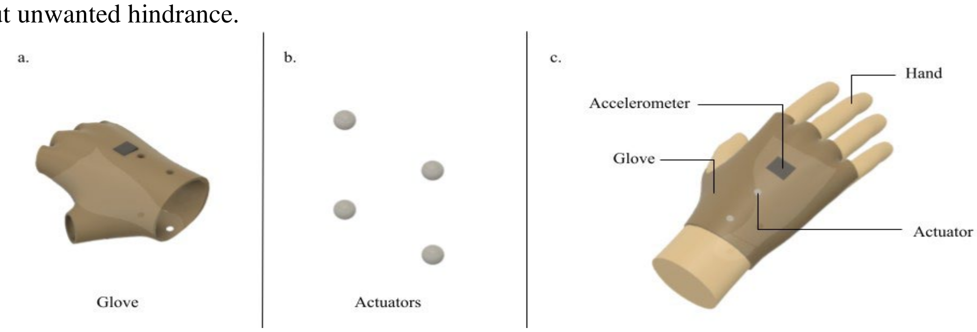

Figure 2: (a) Conceptual model of glove. (b) Conceptual model of actuators. (c) Assembled full model of actuators in glove on hand.

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Design and Materials

Our assistive soft robotic wearable device for hand tremors is a fingerless glove that covers the palm and wrist area down to just below the wrist joint. This will allow for the free movement of the fingers while also minimizing constraints on the forearm. The glove also has four small holes in the appropriate locations to allow space for the actuators to make contact with the wearer's hand. Four pneumatic actuators are located on the hand and wrist's top and bottom sides. Each pneumatic actuator is an inflatable silicon sphere with a diameter of 7.5mm. The actuator's small size will minimize unnecessary bulk and visibility. The miniature accelerometer used to detect tremor motion is located on the back of the hand.

The glove's body is made of a 65% cotton, 35% polyester blended fabric. This blend is breathable, soft, and comfortable while also having some stretch and durability (Islam et al., 2019; Ozdemir, 2017). Additionally, it is not only affordable but also easy to manufacture, including a variety of colors and patterns. The pneumatic actuator is made of silicon to facilitate stretchability, generating force when actuated and maintaining flexibility when not actuated during normal movement. Moreover, due to its soft, compliant nature, silicon is highly compatible with the human body and therefore safe for wearable applications. Figure 2 shows conceptual 3D CAD models of the glove and actuators separately as well as a full, labelled concept model of our device on a human hand.

Tremor Detection Method and Closed-loop Control System

Figure 3 shows a conceptual overview of our proposed tremor control system. First, the accelerometer located on the back of the wearer's hand senses the motion of the hand as a sinusoidal function with a specific amplitude and frequency. Hand tremor motion has a higher frequency and amplitude than normal hand motion. Based on this, we input the measurements from the accelerometer into an algorithm such as a Fast Fourier Transform (FFT) to identify significant persistent hand motion between 2Hz and 15Hz, which indicates that the wearer is experiencing hand tremors. If this is determined, a constant force command is given to the actuators, causing them to make and maintain contact with the hand. In addition, the sensor data from the accelerometer goes through a position estimator, which double integrates the measured acceleration to obtain the hand's estimated position. The position values are then passed into a PI controller that determines the magnitude of counter force needed to effectively reduce the hand motion's amplitude. The output from the PI controller is added to the constant force command going to the pneumatic actuators. As this is a closed-loop control system, the accelerometer continually senses hand motion, and the actuation process continues as necessary.

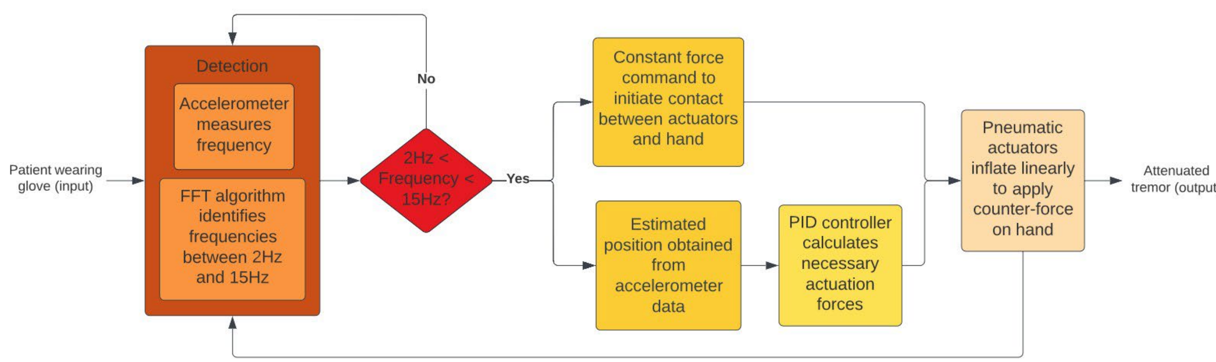

Figure 3: Conceptual control system block diagram for glove device.

Actuation Method

Our actuation method uses miniature silicon pneumatic actuators. We designed two actuators on the back of the hand and two on the palm side of the glove, one located below the wrist joint and one above in each case. Each actuator is a sphere with a diameter of 7.5mm when inflated. When actuation occurs, the pneumatic actuators inflate, and the silicon expands towards the wearer's hand to apply the correct force onto either side of the hand and wrist to counteract the tremor motion. As a result, the movement of the hand in the vertical axis is significantly limited, while other degrees of freedom are maintained to allow the user adequate hand mobility. A miniature pneumatic pump can be used on the back of the glove to provide the necessary inflation air for the actuators. Additionally, a small controller chip can be included to modulate the pressure supplied by the pump.

Device Simulation

To model our solution, we used Matlab with the Simulink and Simscape Multibody add-ons. Figure 4 shows our simulation setup in Simulink, and the simulation parameters are detailed in Table 1. First, we modelled an average-sized human hand and wrist in the 3D CAD software Fusion 360. We assumed the mass of the hand to be 400g and the mass of the wrist to be 200g (Kaye & Konz, 1986). We then imported these CAD models into Simulink as solid bodies. Next, we simulated the tremor motion in hand as a sinusoidal function with an amplitude of ±8.0mm and a frequency of 8Hz. These parameters are similar to those discussed by Daneault et al. (2013). We modelled the tremor motion as linear oscillations occurring only in the vertical direction. That is, if the hand was held out with the palm facing down, the tremor would cause the hand to move up and down, as depicted in Figure 1a. We ignored the rotation of the hand relative to the wrist because the amplitude of angular motion was assumed to be negligibly small. In our simulation, the hand moved vertically while the wrist stayed stationary to simulate tremors contained in hand alone and not the forearm. Next, we created a 3D CAD model of the glove using Fusion 360 and imported it as a solid body into Simulink, positioning the glove onto the hand in the simulation. The hand, wrist, and glove are connected through spatial contact forces. Although the components were modelled as solids, the Simulink contact force model allows for some deformation during contact.

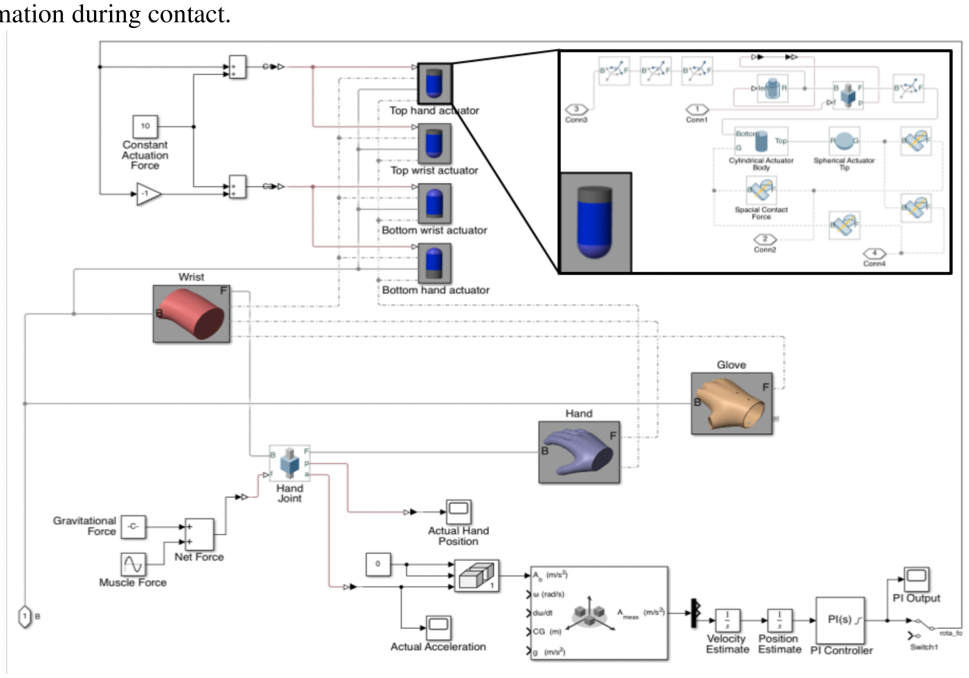

Figure 4: Simulink experimental setup. The box in the top right corner shows the Simulink experimental setup behind the mask of one actuator.

Table 1: Simulation parameters.

Mass of hand	400 g
Mass of wrist	200 g
Mass of glove	75 g
Mass of one actuator	1 g
Amplitude of hand tremor before actuation	± 8.0 mm
Frequency of hand tremor before actuation	8 Hz
Hand joint spring stiffness	1 N/m
Hand joint damping coefficient	40 N/(m/s)
Contact force spring stiffness	1e9 N/m
Contact force damping coefficient	1e3 N/(m/s)
Contact force coefficient of static friction	0.5
Contact force coefficient of dynamic friction	0.3
Natural frequency of accelerometer	40 Hz
Damping ratio of accelerometer	0.707
Constant input force to actuators upon activation	10 N
Controller proportional gain	4 N/mm
Controller integral gain	80 N/mm-sec

We then modelled the pneumatic actuators as a spherical solid with a diameter of 7.5mm. Although our concept for a physical model of the glove includes actuators that are only spheres, for the purposes of our simulation we attached this sphere to the tip of a cylinder with the same diameter and a length of 20mm to visualize the actuators more clearly in the simulation. When given an input force, the actuators move linearly towards the hand, and a cylinder at the base of the model actuators with the same diameter of 7.5mm and a variable length grows to represent the pneumatic inflation process. We applied spatial contact forces between the actuators and the hand and wrist to simulate the forces applied by the actuators onto the hand and wrist to attenuate hand tremors when actuation occurs.

Next, we added an accelerometer model. The measured acceleration of the hand from the accelerometer goes through two integrators to create an estimate of hand position during tremors. This estimate is input into a PI controller. The PI controller applies a proportional gain of 4 N/mm to produce the necessary counterforce and an integral control gain of 80 N/mm-sec to keep any residual tremor motion centered around the hand's equilibrium position. The output of the PI controller is added to a constant input force of 10N, which causes the actuators to maintain contact with the hand, and the resulting total force is the input force to the actuators.

With the hand, actuator, and accelerometer dynamic model parameters we selected, we were able to achieve sufficient tremor reduction without requiring the use of any derivative gain in the controller. In order for all actuators to oppose the direction of hand tremor motion, the force command for the bottom actuators must be opposite in sign than the top actuators. To accomplish this, the output value of the PI controller going to the bottom actuators is multiplied by a gain of -1. The actuators applying a force based on the PI controller onto the hand and affecting its motion amplitude make this a closed-loop control system. Figure 5 shows each solid part used in our simulation and the entire simulation model rendered by Simscape.

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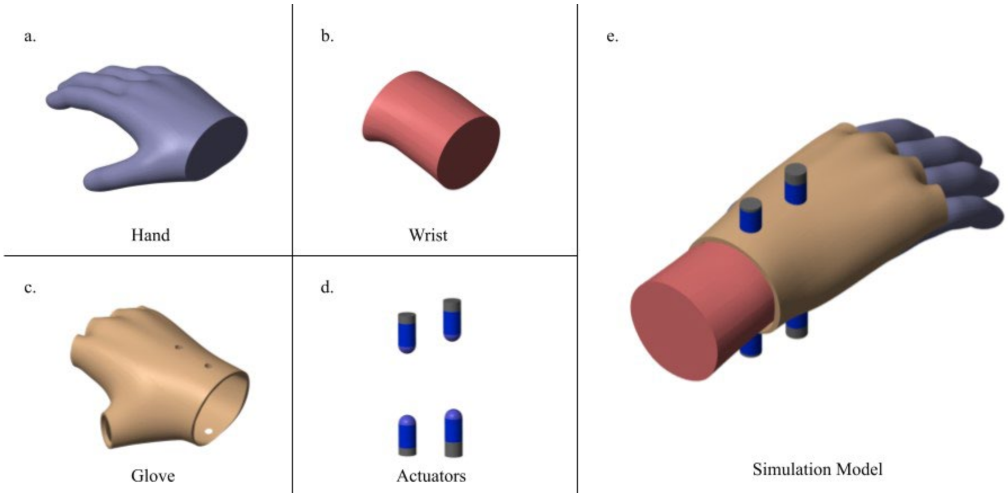

Figure 5: Simulink components: (a) Hand solid. (b) Wrist solid. (c) Model glove. (d) Extended actuators for simulation. (e) Assembled model hand, glove, and actuators in Simulink simulation environment. Actuators are shown inflated towards the hand.

Results

To validate our simulation and understand the effectiveness of the proposed approach, we employed a succession of four simulation test cases. Based on our simulation results, our proposed glove, actuators, and closed-loop control system design successfully attenuated the amplitude of hand tremors to an acceptable level that would not hinder the wearer's ability to complete tasks with their hands. Table 2 summarizes the resulting tremor amplitudes for each of our four simulation cases, and Figure 6 shows a graphical comparison of the tremor amplitudes of the baseline run and our final simulation case.

Our baseline case modeled a hand tremor with no glove or actuators with an amplitude of ±8.0mm, a magnitude of hand tremor motion that would decrease a patient's quality of life. Our second simulated test case included the actuators and employed only the constant activation force of 10N, without the PI controller. This case represents an open-loop, semi-active system. In this case, the actuators exert a continuous force on the hand but do not receive continuous feedback data from sensors on the hand. The spring stiffness of the actuator model introduces a spring force opposing the tremor motion of the hand. Additionally, the constant actuation force produces a net force that continuously opposes the direction of hand motion, effectively increasing the spring stiffness of the actuators. Due to these combined opposing forces, the amplitude of hand tremor was reduced to ±5.2mm, a 35% reduction relative to the uncontrolled tremor.

Next, we simulated our closed-loop, active system that includes the actuators with the PI controller. To first determine whether an "ideal" PI controller could be effective, we used actual hand position instead of the accelerometer-derived hand position estimate as the input to the controller. We achieved this by directly accessing the hand's actual position from the Simulink joint model. This represents an ideal environment as it does not rely on physical sensors such as an accelerometer to gather data about the hand motion. This ideal case produced a significantly reduced amplitude of motion of ±1.8mm, establishing an upper bound on the achievable performance for our active control system design.

Our final simulation case was based on our complete, closed-loop, active system that included the actuators, accelerometer, and PI controller. In this case, the accelerometer model included dynamic lag. This time, we implemented a hand position estimator by double integrating the measured acceleration from the accelerometer. This produced a more realistic performance assessment by including the adverse impact of the dynamic lag within the accelerometer.

The resulting amplitude of hand tremor motion was ±2.0mm. This level of tremor attenuation was considered to be a successful outcome. Moreover, the decrease in amplitude between the semi-active and active systems indicates that a dynamic solution to attenuate hand tremors can be significantly more effective than a semi-active solution.

In our PI controller, we used a proportional gain of 4 N/mm, an integral gain of 80 N/mm-sec. The proportional gain produces a counterforce to further reduce the tremor amplitude, while the integral gain acts to "center" the hand motion around a value of zero to compensate for the effect of gravity on the hand. Running our simulation with integral gains lower than 80 N/mm-sec was not effective in centering the remaining hand tremor motion after actuation around the hand's equilibrium position. Increasing the proportional gain increases the efficacy of the control system in attenuating the amplitude of hand tremors; however, when increasing the proportional gain to 5 N/mm the closed-loop system began to exhibit signs of instability. Therefore, we concluded that a proportional gain of 4 N/mm was an adequate value to demonstrate the success of the system at reducing the amplitude of hand tremors while maintaining a stability margin.

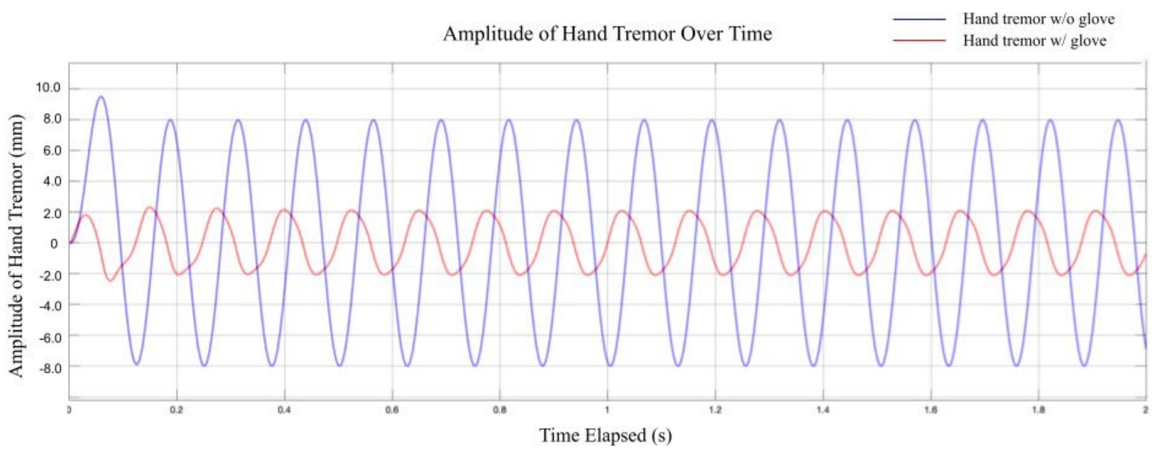

Figure 6: Graphs showing the amplitude of tremor motion measured by the position of the hand over a two second interval. The blue graph shows the hand amplitude without the implementation of our glove device, and the red graph shows the hand amplitude with our device implemented.

Table 2: Simulation results showing amplitude of hand motion for four test cases.

	Actuators	Control loop	Accelerometer	Amplitude
Case 1: Baseline				±8.0mm
Case 2: Semi-Active	P			±5.2mm
Case 3: Active Ideal	P	P		±1.8mm
Case 4: Active Realistic	P	P	P	±2.0mm

Discussion

We have presented an innovative design for a wearable glove that uses soft robotics and a closed-loop control system to attenuate tremors in hand. We used Fusion 360 to create solid hand, wrist, glove, and actuator models. We then used Matlab, Simulink, and Simscape to simulate our active device and experiment with different parameters to optimize the efficacy of our solution. Our baseline simulation was a 400g human hand tremoring in the vertical direction with an amplitude of ±8.0mm and a frequency of 8Hz. Based on our simulation results, our active glove design with two pneumatic actuators on the top and bottom of the hand and a closed-loop control system that implements an accelerometer, position estimator, and PI controller successfully attenuated the hand tremor motion to an amplitude of ±2.0mm in a realistic simulation environment that accounts for dynamic lag in sensor measurements. The 75% reduction of hand tremor amplitude would allow the wearer to use this hand to complete everyday tasks. As a result, our soft-robotic glove solution to hand tremors would successfully increase the user's quality of life.

Our design improved current hand tremor treatments because it is non-invasive, active, and uses soft-robotic materials to increase patient comfort and safety. Current invasive treatments such as primidone have many unwanted side effects and are often less than 60% effective (Deuschl et al., 2011). Several current semi-active, non-invasive treatments for reducing hand tremors exist. However, these solutions do not actively respond to the specific tremor motion the patient is experiencing and are significantly less successful in tremor suppression (Kalaiarasi & Kumar, 2018). Based on our simulation results, we confirmed that eliminating the active component of our solution to make it semi-active does not reduce hand tremor amplitude as effectively as an active control system, resulting in only a 35% reduction with an amplitude of ±5.2mm. Lastly, unlike most current wearable solutions that use bulky and highly visible actuation devices (Manto et al., 2007), our device uses soft robotics and pneumatic actuators to increase compatibility with the human body and produce a more comfortable and minimal wearable device.

One limitation of our study is that we modelled the hand tremor motion as translational linear oscillations of the hand in the vertical direction. Although it is unlikely that this change would significantly impact our glove's performance, a more precise future model may simulate the hand tremor motion to include a small-angle rotational motion of the hand relative to the wrist. Another potential limitation is that, for our study, we simulated a hand tremor with an amplitude of ±8.0mm. However, based on our research, patients with hand tremors could experience tremors with amplitudes as large as ±10.0mm. Consequently, future continuations of this research could simulate our device with different starting tremor amplitudes. In future work, we will investigate the effects of other imprecisions within the system, such as measurement noise and scale factor errors in the accelerometer. Future studies relating to our research may also experiment with different combinations of proportional, integral, and derivative gains to further optimize our control system. Moreover, our simulation began once a hand tremor had already been identified to initiate the active control system. Future simulation work could implement the tremor detection method defined conceptually in this paper, such as using an FFT algorithm to detect specific frequencies of motion. An additional limitation of this study is its simulation-based environment. We have used simulations to demonstrate the success of our concept; however, in the future we hope to construct a physical prototype of our glove and test it in a real-world setting with actual hand tremor patients. Lastly, our vision for future continuations of our research may include exploring additional applications of our concept to attenuate tremors in other areas of the human body.

Conclusion

Tremors in the hand are a common medical condition that significantly decreases the patient's quality of life. Many currently available treatments and ongoing research for hand tremor solutions are either invasive or bulky and highly limiting wearable devices that contribute to the negative social impacts of hand tremors on a patient's life. In this study, we have presented an innovative wearable solution that uses small, soft robotic pneumatic actuators to successfully attenuate hand tremors in their direction of motion while still allowing the wearer a complete range of motion in all other directions. The soft robotic, comfortable materials incorporated in our design increase safety and comfort while wearing our glove device. We implemented a closed-loop control system that uses an accelerometer and PI controller to actively respond to the wearer's hand tremor and actuate accordingly. Based on simulation results, we reduced the amplitude of tremor motion by 75% to ±2.0mm, a value small enough to restore the user's ability to complete daily tasks. As a result, our solution can improve several aspects of a hand tremor patient's quality of life.

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