FinePose: Fine-Grained Postural Muscle Profiling via Haptic Vibration Signals

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ABSTRACT

As people's lifestyles becomes more sedentary, neck and back pain amongst young adults have increased. Those who spend a significant amount of time looking at digital screens (e.g., computers, tablets, smartphones) tend to assume forward head postures (FHP), which increases the load on their postural muscles and stress on the cervical spine. As a result, FHP often leads to neck and upper back muscle pain and interferes with normal functioning and quality of life. It may also result in degenerative spine issues, such as cervical degenerative disc disease and cervical osteoarthritis.

We present *FinePose*, a system that measures postural muscle (upper and middle trapezius muscle) stiffness levels. *FinePose* repurposes the haptic vibration input on existing smart posture braces, generated by the lightweight and low-power coin vibration motor, and conducts active vibration sensing to measure the muscle elasticity. It uses an array of accelerometers at different distances from the motor to capture vibration response. Next, *FinePose* extracts features that describe vibration propagation properties and establishes a regression model to predict the muscle stiffness level. We conduct real world experiments with four subjects on different days, and demonstrate preliminary results that validate *FinePose*'s feasibility.

CCS CONCEPTS

• **Human-centered computing → Ubiquitous and mobile computing**.

KEYWORDS

Sedentary lifestyle; Wearable device; Posture assessment; Haptic vibration; Muscle stiffness sensing

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1 INTRODUCTION

As people's lives become more sedentary, back and neck pain are increasing. It is reported that as of 2021, about 40 percent of adults in the United States between the ages 18 and 30 experience symptoms of back and/or neck pain [20]. This is a 15% increase from 2010, which means that more people are starting to experience pain at a younger age [38]. In the USA alone, medical spending on back and neck pain related issues is 134.6 million dollars [9]. This is largely due to the rise and proliferation of desk jobs and usage of digital devices (e.g., computers, tablets, smartphones), which encourage people to stay seated for long periods of time. It is estimated that the average a person stays seated for up to 10 hours each day. During COVID-19 lockdown, recent study on 818 participants shows that sitting time is increased by 43.6% on weekdays and 121% at weekends [13]. While sittings, a person generally holds a position that protracts the head and flexes the spine, which is referred to as the forward head postures (FHP) [27].

When a person holds the forward head posture, their deep neck muscles are weakened, and the upper trapezius' postural load increases, as depicted in Figure 1. This often manifests as muscle stiffness and causes the neck and back pain [38]. However, it is difficult for large superficial muscles, such as upper trapezius muscle, to maintain the forward head posture for prolonged periods of time (e.g., a few hours). To compensate this excessive load on muscles, fascia regulates its stiffness to provide support. However, as fascia being constantly called to compensate, fascial fluid becomes more viscous, presenting as persistent stiffness [15]. This chain reaction of compensations creates a cycle of increased stiffness and immobility. Hence, monitoring the progression of this stiffness in fine-grained is important to design effective feedback mechanisms and other preventive methods to correct users' posture, preventing back, neck and legs pain.

Prior work on posture correction involves correcting the angle of spine and torso by the use of a back brace [33] or detecting and providing feedback for people to sit straight [32]. Neck and back muscles work in tandem to maintain posture. Therefore, correcting only the spine's angle dismisses the neck's role and may still lead to the development of fascial adhesions and pain [27]. Other muscle sensing methods involve the use of Electromyography (EMG), Mechanomyography (MMG) and shear wave elastography (SWE) methods [8, 23, 24, 34, 36]. EMG measures the muscle activity by the change in its electrical activity, i.e., the change in nerve simulation in muscles [8, 34]. MMG measures the low frequency muscle fiber oscillations during contraction to infer fatigue [23, 24]. While these methods are effective for profiling phasic of muscle activities,

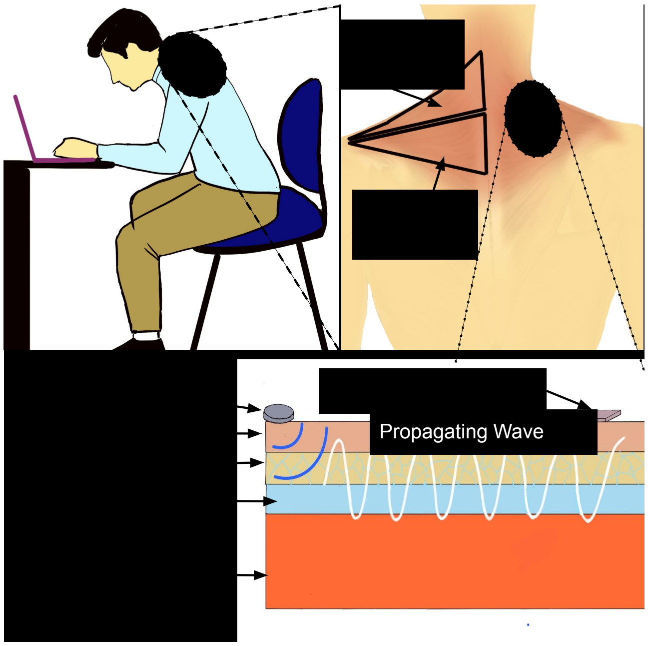

Figure 1: Motivation and intuition of developing *FinePose*. Forward head posture impacts trapezius muscle and fascia stiffness, leading to back and neck pain. *FinePose* profiles stiffness using haptic input and accelerometer array embedded on a regular back brace.

they are not suitable for postural muscles due to different ratios of muscle fiber types.

In this project we propose *FinePose*, a system that measures the trapezius muscle stiffness level based on muscle vibration responses to provide detailed and intuitive information about the users posture. In particular, *FinePose* includes an active vibration source (a coin motor), which is commonly being used to provide haptic feedback [32], to measure how the muscle responses to a known vibration source [2] to infer stiffness levels of trapezius muscle fine-grained. Intuitively, surface vibration propagates through the skin and closer layers of superficial fascia and shallow muscles, as shown in Figure 1. Then, *FinePose* uses an accelerometer array to capture and characterize motor vibration at different distances and profile muscle stiffness.

However, realizing the solution is difficult due to the following **challenges**. (1) Literature on muscle monitoring only focus on phasic muscles, the feasibility of postural muscle monitoring is little known. (2) It is unclear what is the most suitable sensing method, where to place the sensors and/or haptic feedback, and how the sensors are distributed and organized to achieve the desired sensing goals.

In this project, we make the following **contributions**.

- To the best of our knowledge, this is the first work to monitor fascia stiffness level of trapezius muscle in fine-grained using wearable device.
- We design *FinePose* to re-purpose the haptic vibration input as an active sensing source to characterize the stiffness levels of trapezuius muscle.
- We conduct real world experiments on four participants who wear *FinePose* at multiple scenarios and the preliminary results to show the feasibility our design. .

2 BACKGROUND

Posture is characterized by the interactions that occur between the skeletal and muscular systems; where one provides structure and the other provides support. The most ideal posture is one that "minimizes stress within available structures" by taking into account a person's muscle activation with respect to their neck, spine, and pelvis positioning [12].

Types of Muscles. There are several muscle groups involved in maintaining posture; how long a certain posture can be maintained is dependent on the distribution of activation amongst those muscle groups. Muscle function is largely dependent on the muscle fibers that make up a particular muscle. Broadly, muscle fibers are either slow-twitch or fast-twitch, each having a different mechanism to produce force. Fast twitch muscles fibers, found in the biceps for example, produce large amounts of force in small bursts, ideal for movement. Slow twitch muscle fibers, on the other hand, are fatigue resistant and are able to produce smaller amounts of force for longer periods of time. [5] The trapezius in particular, contains different proportions of slow twitch and fast twitch fibers in different regions. The upper trapezius is responsible for facilitating neck, head, and shoulder movement and contains a higher proportion of fast twitch fibers than the middle and lower trapezius [10]. FHP often require these fast twitch fiber being excessive activated, which leads to the muscle stiffness in the upper trapezius area [7].

Fascia and Muscle Stiffness. Persistent stiffness is an indication of muscle overactivation, which results in the thickening of fascial connective tissue called fascial adhesions [27]. Fascia is a connective network of tissue enveloping muscle and the skeleton; it is meant to provide support to surrounding muscles by changing its viscosity [35]. When a person is sitting, the load is shared by the activated muscles and surrounding fascia. As muscles become more and more fatigued, the fascia is able to shift from a sol to gel to take on more load. When a person is in the FHP, their overactivation of the fast twitch muscle leads fatigue easily, which can lead to the fascia stiffness in a few hours [22].

3 SYSTEM OVERVIEW

FinePose measures stiffness levels of the trapezius muscle by observing its vibration responses via light-weight wearable system with haptic-based active vibration sensing as shown in Figure 2. *FinePose* leverages a tiny haptic actuator and an array of accelerometers to monitor how the muscle reacts to the haptic input and then infers muscle stiffness levels. *FinePose* consists of two main modules: the *Active Vibration Sensing (AVS) Hardware* and *Muscle Profiling (MP) Software*. *AVS* includes a low-cost, programmable, and low-power haptic input and a lightweight sensitive vibration acquisition hardware. *MP* module includes algorithms to pre-process the data obtained from the *AVS* hardware, extract main features, and predict

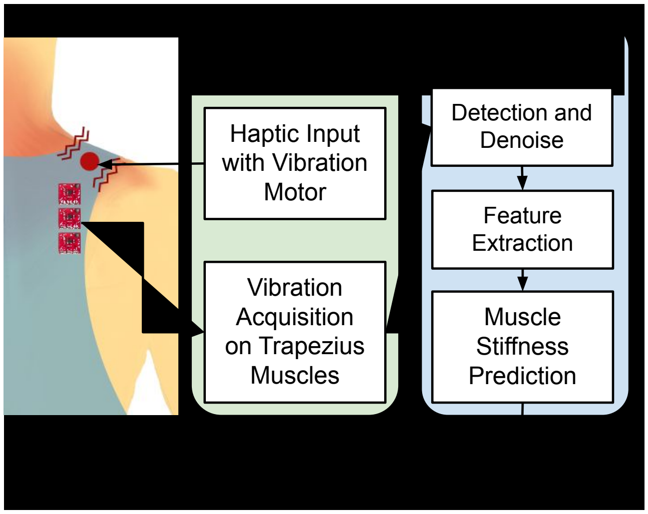

Figure 2: *FinePose* System Overview. As muscle and fascia stiffness increases over time, changes in elasticity will impact the haptic input signal's properties. These waves will be captured by a series of accelerometers placed at different distances from the haptic source.

the muscle stiffness level. The detailed design and implementation of the two modules are described below.

3.1 Active Vibration Sensing Module

To model the muscle stiffness with the vibration propagation model, *FinePose* first generates a known vibration signal via haptic input – a coin vibration motor. To re-purpose the haptic feedback, the model uses signals generated by the vibration motor, which is commonly used by the spine angle based posture correctors, to give haptic inputs. The haptic input is designed to be a I second vibration followed by I' second of interval, which is common in existing posture braces that provide feedback.

This vibration signal propagates through the trapezius muscle and is captured by a series of acclerometers placed in an array, as shown in Figure 2. Intuitively, when the muscle stiffness level is high, the superficial fascia is more viscous or stiff. Which increases the elasticity and allows vibration signals to travel longer distances with less decay [1]. The sensor array consists of three accelerometers placed at different distances from the vibration motor. The signal captured by the accelerometer (Figure 4) consists of the body movement, intrinsic vibration in the muscle, as well as the haptic input vibration. Because the haptic feedback generated by vibration motor is a surface wave [2], *FinePose* acquires the acceleration of axis parallel to trapezius muscle surface. The accelerometer array is placed one inch away from source, and the three accelerometers in the array are placed one inch apart from each other. The array collects the change in haptic input at different distances.

This signal is then forwarded to the Muscle Profiling Module (Section 3.2) for further denoising and information inference.

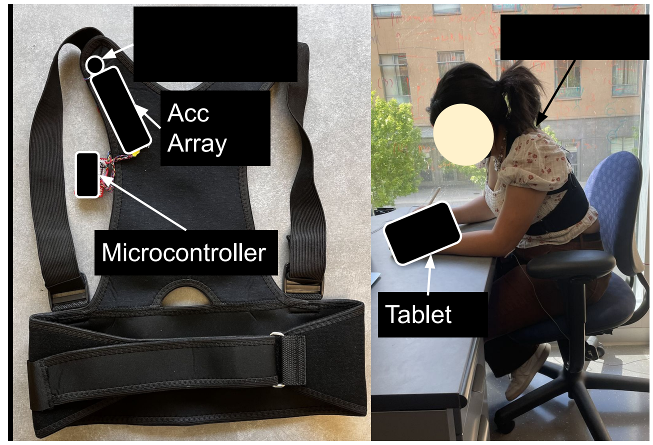

Figure 3: *FinePose* hardware and the experiment setup.

3.2 Muscle Profiling Module

To extract haptic input vibration for muscle stiffness profiling, *FinePose* first conducts signal processing. Next, it extracts features from the event signal. Finally, it establishes models to predict the muscle stiffness level.

Signal Processing. *FinePose* applies a sliding window on the absolute values of the signal $s_{abs} = |s_{raw}|$ and calculates the average value in the j^{th} window w_j. We can consider w_j as the smoothed signal s_{abs}, which retains large changes in s_{abs} and indicates vibration events. Then *FinePose* conducts peak detection on w_j and extracts the indexes of the highest values for the k^{th} peak p_k. To accurately detect the start and end of the event, we calculate a threshold of event as a weighted average $Th_e = 2/3 \times w_{avg} + 1/3 \times p_{avg}$ (obtained from empirical research), where $w_{avg} = \sum_{j=1}^{J}(w_j)$ and $p_{avg} = \sum_{k=1}^{K}(p_k)$. *FinePose* consider the $j^t h$ windows with $w_j >= Th_e$ and $w_{j-1} < Th_e$ as the event's onset. Since we know the haptic input vibration length Len_e, *FinePose* extracts Len_e of signal starts from w_j as the event.

Figure 4 shows the extracted signal segments, where the grey line depicts the raw vibration signal, and the portions highlighted in red depict the detected event. Since the accelerometers capture the signal coupled with human torso motion, intrinsic muscle vibration, and the haptic input vibration, *FinePose* applies a high pass filter on the detected event signals to remove the noise of body motion (0-10 Hz) and the muscle intrinsic vibration (10-40 Hz)[23].

Feature Extraction. Filtered event signals from the accelerometer array are used to generate features.

(1) Autocorrelation. Autocorrelation describes the periodicity of the signal [6]. Since *FinePose* measures the known haptic vibration, the changes in the signal periodicity can be used to indicate the muscle stiffness changes. For i^{th} sensor's event signal $s_i, i = 1...N$, we calculate the autocorrelation of the signal as $C_\tau = \frac{1}{T}\sum_{t=1}^{T-\tau}(s_i(t) - \bar{s_i})(s_i(t+\tau) - \bar{s_i})$, where T is total number of sample in the signal, $s_i(t)$ is the sample value at t and $\bar{s_i}$ is the mean of all the sample values in the signal s_i [6]. From this, we extract the maximum autocorrelation values $auto\_val_i = max(C)$, and the corresponding lag value $auto\_lag_i = \arg\max_\tau(C)$.

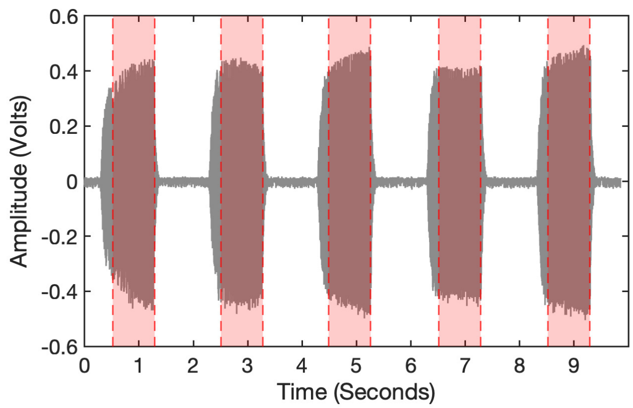

Figure 4: Signal event detection example.

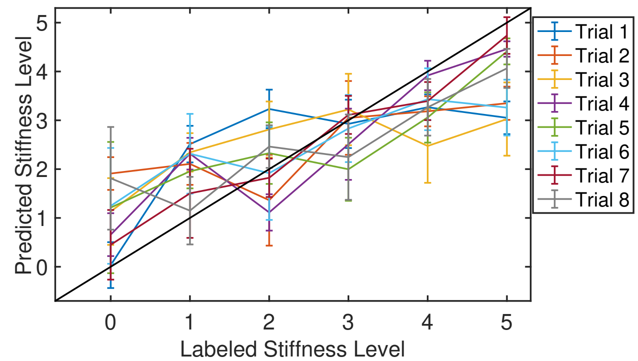

Figure 5: Stiffness level prediction by *FinePose* vs the labeled stiffness level in 8 trials (4 subjects 2 days).

(2) Frequency-Elasticity Characteristics. The shear wave frequency changes with elasticity of the propagation media [2]. To describe frequency characteristics, we first detect the frequency bin with the highest energy as the dominant frequency f_{dom}. Then we extract the frequency band $f_{dom} - f_{con}$ to $f_{dom} + f_{con}$ so that the signal energy in this band is ec of the total signal energy ($ec = 25\%, 20\%, 15\%, 10\%, 5\%$). We consider $freq\_ec$ describes the signal frequency distribution characteristics and use it to profile the elasticity changes.

(3) Pairwise Ratio of Signal-to-Noise Ratio (SNR). To characterize the decay model change over different muscle conditions, *FinePose* also calculates SNRs of s_i as snr_i, and uses the ratio $r_{i,j} = snr_i/snr_j$ for each pairwise sensor as features.

The feature vector $\mathbf{x}$ concatenates $auto\_val_i$, $auto\_lag_i$, $freq\_ec_i$, $r_{i,j}$ for all i^{th} and j^{th} sensors in the array.

Stiffness Level Prediction. The feature vector $\mathbf{x}$ and the label of the muscle stiffness level y is then fit to a linear regression model $y = a\mathbf{x} + b$. The ordinary least square method is used to estimate the parameter a and b [11]. For the unlabeled data $\hat{\mathbf{x}}$, *FinePose* predicts the stiffness level of the muscle $\hat{y} = a\hat{\mathbf{x}} + b$.

While preliminary results (Section 4) using linear regression are encouraging and demonstrates the feasibility of the design, there are still underlying challenges that need to be solved: 1) robust to multiple layers of clothes, 2) robust to user variance, and 3) robust to physical condition variance (e.g., before/after exercise). We plan to explore domain adaptation regression and/or combining physical and data-driven model to further enhance the robustness of the stiffness level prediction model.

4 EVALUATION

Experimental Setup. We conduct real-world experiments and preliminary analysis. We collect four subjects' data, two males and two females on two different days (8 trials in total) based on the IRB protocol reviewed and approved by the Office of Research Compliance and Integrity, University of California, Merced. The subjects selected are between the age group between 18 and 26, with heights range from 165 cm to 172 cm.

To ensure the muscle stiffness for each trial starts from a baseline stiffness, the subject completes a series of low impact exercises to break up short term, daily fascial and/or muscle stiffness. The exercises include (1) head tilt stretch, (2) doorway perctoral stretch, and (3) over arm shoulder stretch. The subject completes three sets of each exercise on both sides for 20 seconds. After stretching, the subject lies down for 10 minutes to relax their neck and back as much as possible. After this, we consider their muscle stiffness to be 0 (stiffness baseline). Next, subjects wear *FinePose*, as shown in Figure 3, where the vibration motor and the accelerometer array are positioned on the upper and middle trapezius muscles with only one layer of fabric in between. The subject sits down using a tablet for 50 minute in their natural posture. We activate *FinePose* to collect 1 minute of vibration data using haptic vibration input every 10 minutes. The muscle stiffness's level defined in increments of 1 every 10 minutes, i.e., the data collected at 10 minutes is labeled as level 1, and the data collected at 20 minutes is labeled as level 2, and so forth. We conduct the data collection procedure for each subject on two different days, resulting in a total of eight trials.

Preliminary Results. We train a linear regression model for each trial. For each trial each muscle stiffness level, *FinePose* extracts 30 vibration events. We sample 67% (20 events) for training and the rest for testing. Figure 5 shows the prediction results with 10-fold cross validation. The x-axis represents the labeled muscle stiffness level, and the y-axis shows the mean predicted values for each respective muscle stiffness level, with the error bar representing the standard deviation. Our preliminary results show that our system is able to detect the positive correlation between the time a person is sitting and their muscle stiffness. We also observed that rate of change in muscle stiffness can differ between each day and between each person. While preliminary results are exciting, we observe multiple challenges to overcome to improve the usability of *FinePose*. We describe future research directions to tackle these challenges in Section 6.

5 RELATED WORK

Haptic Input. Haptic input enables interaction via touch, and vibration has been used in various use cases [21]. It has been explored for gaming [3] and assistive technologies hearing or in robot assisted surgery[28–30]. They are often adjusted to simulate an actual physical encounter, and therefore reinforce what is happening on the screen or in the real-world for the users. In these systems, haptics are used solely as the mean for providing input/feedback to users. We repurpose the haptic input vibration as the source for active vibration sensing of the user.

Muscle Fatigue/Activation Monitoring. Muscle activation and fatigue have primarily been studied using electromyography (EMG) and mechanomyography (MMG) measurements. EMG measures electrical signals sent from the brain to muscle, causing them to contract. The signal's frequency is associated with how activated the muscle is; as nerve signals are transmitted at a higher frequency it causes muscle to contract more [31, 34]. Therefore, prior work using EMG, primarily focuses on high impact movements requiring the use of type 2 muscle fibers, in order to generate large enough signals. MMG measures innate muscle vibrations, and changes in these vibrations. are used to characterize contraction. However, prior work using MMG also focuses on skeletal muscles, such as the bicep or calves, that are able to generate large enough vibrations when performing high impact movements [23, 25]. During prolonged sitting, however, fewer muscle fibers are recruited by the brain's signals and innate vibrations are minimal. Therefore, EMG and MMG sensing is not ideal for postural activation.

Shear Wave Elastography (SWE) Shear wave elastography is a technique that uses ultrasound imaging to measure shear wave propagation generated by an ultrasound probe. Obtaining the velocity of these waves, allows for the direct calculation of Young's modulus - a measure of stiffness characterized by strain and stress factors. Shear wave elastography is able to provide reliable and accurate measurements of muscle stiffness. However, the technology has only been used in clinical settings - with access to large mechanical vibrators and sterile conditions [14, 36]. Therefore, while effective, this technique is costly and impractical in home settings. Instead, we choose to implement the underlying principles of shear wave elastography in a more accessible form factor using accelerometers and a vibration motor.

6 DISCUSSIONS

We present *FinePose* as an attempt to use the haptic vibration input and accelerometer array to profile trapezius muscle stiffness. We further discuss the limitations of the system and future directions.

Wearability and Garment Integration. The current system uses a back brace as the form factor for the sensing system. This setup helps to maintain a tight contact between the sensor/motor and the back of subject. However, the use of the brace for long periods of time can be uncomfortable and is not aesthetically pleasing. In the future, we plan to work on making the system with higher wearability by weaving the circuit into fabric[19] and using IMU with smaller form factor[4, 37]. This will improve the system's comfort level and will make it discreet and feasible for sensing over long periods of time. However, this higher wearability also makes accurate muscle condition inference more difficult. Because of activity and movement of the subject during sitting, the sensors position may change and this will change the coupling between sensor and subject's back. This change may cause the sensing data distribution shift, and result in muscle stiffness prediction error.

Indirect Inference for Other Postural Muscles' Conditions.

Here we explore the feasibility of our system to measure the trapezius muscle stiffness by conducting the preliminary experiments on one side of trapezius muscle We plan to explore monitoring on both sides to infer a holistic profile of the sedentary posture. For example, when there is an imbalance load between the left and right trapezius muscles, the fascia develop on both sides may vary too. The measurements from two sides would allow us to further infer other postural muscles' imbalance and irregularities.

Personal v.s. General Muscle and Fascia Stiffness Models.

Due to physiological differences between participants (eg. body mass index, weight, etc.)each person's body type and muscle condition varies [18]. Furthermore, postural muscle stiffness is also affected by routine in long term, sitting habits, and age. For example, the elderly have increased muscle stiffness compared to younger adults [16, 17]. Additionally, differences in sleeping patterns and daily activities can change the rate of change in stiffness on a particular day [26]. Our preliminary results demonstrate the feasibility of using personal model in Section 4. Despite our best efforts to set the trapezius stiffness to a baseline, each trial still had variations in initial muscle stiffness - which requires further investigation to create a more robust and general model of muscle stiffness.

Optimal Sensor-Actuator Placement For Postural Profiling.

Our current setup uses a back brace with an accelorometer array and vibration motor sewed in to keep the system in close contact with the trapezius muscle. Between each subject, upper body sizes may vary, thus affecting which portion of the trapezius is being measured - this is important since muscle fiber content, direction, and function changes between the upper, middle, and lower trapezius. We will address this by exploring more adjustable form factors.

Optimal Human-in-the-Loop Feedback Control to Enhance Healthy Posture.

Our current system uses the vibration motor to generate haptic input events, which is captured using an accelerometer array to the predict muscle stiffness level. Currently our system repeats 30 vibration every 10 minutes, which is not an ideal interaction with the end user since it interrupts their activities. In future we plan to minimize the haptic intrusion required for the system to work. Additionally, currently our system only gathers information through haptics. After minimizing the amount of vibrations necessary to gather information, we would like to explore how this can also serve as feedback to the user.

7 CONCLUSION

In this paper, we present *FinePose*, a system to detect muscle stiffness levels via active vibration sensing. We re-purpose the use of haptic input from common posture corrector to profile the stiffness level of the trapezius muscle and fascia. We conduct real world experiments on four subjects and the preliminary results show the feasibility of our system design on personalized models. In the future, we will optimize the system and enhance generalizability of the model.

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