博士(人間情報学)論文概要

Embodied Interfaces for Sensing and Augmenting Human Posture Coordination
姿勢調節機能を計測し拡張する身体的インタフェースの研究

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Abstract

Since the industrial age, mankind has become increasingly more sedentary. For the first time in human history we are spending more than 80% of our day sitting down and it is causing detrimental health effects on a global scale. This has widely been attributed to the rapid advancement of technology and its impact on modern spaces. Prolonged sitting increases the chances of posture related problems. Poor posture leads to negative health conditions such as muscular pain and injury, increased risk of cardiac disease, headaches, stress and fatigue. However, on the contrary, good posture has a variety of benefits such as improved physical health, pain prevention, healthy respiration, relaxation and enhanced productivity. Research shows that we as humans acknowledge the posture problem and often make efforts to sit correctly but we tend to quickly fall back into a slouching position as we become immersed in the distractions of everyday life. In the modern world, human sitting behaviour is largely influenced by our supportive structures and social contexts. The chair itself has remained an ancient technology facing little innovation across thousands of years. Human sitting behaviours, the chair and social contexts are all deeply connected. As the advancement of technology proves to be an unstoppable force, so to must the chair evolve through the realms of IoT, to accommodate changes in our modern workspaces and improve the human condition.

My hypothesis is that a user's posture and wellness habits can be positively shaped through an IoT embodied interface that provides real-time feedback and status information. In exploration of this hypothesis I also emphasized the necessity for a human-centric based design in order to implement this platform in real world settings. My vision was to invent a device that was both sophisticated, minimally invasive and ubiquitous in order to seamlessly augment the user's posture coordination without encumbering their daily productivity. In order to augment the user's posture coordination the device required precise real-time classification of the user's posture and an effective non-binary feedback system. I also hypothesized that different spatial haptic cues on the user's back can be used to communicate various types of information about their posture without the need to refer to a visual or audial interface. Through this IoT device I sought to increase the duration of upright posture in order to prevent slouching related problems.

I have developed the LifeChair, a smart cushion for the back of the chair that actively trains the user to sit upright in real time and improve their wellness habits. It does this through sensing the user's posture and providing vibrotactile feedback patterns to notify the user how to fix their posture. The system utilizes my patented eTextile sensing technology which allows for flexible, adaptive and accurate pressure sensing and can be customized to develop sensor interfaces of various shapes and sizes. My developed posture classifier can detect over 11 different sitting postures in real time with over 98.1% accuracy. The LifeChair is also capable of detecting the user's heart rate and respiration rate from their back. This is the only cushion or chair device which is capable of active vitals sign sensing. The LifeChair system pairs with a dedicated smart phone application that provides real time performance tracking. Extensively, I introduced additional wellness features such as stretching, meditation and standing reminders, that utilized the same eTextile technology and human posture models developed in my research.

I designed and continuously improved the posture classifier accuracy through consecutive user studies to reach a threshold-based accuracy of 98.1%. In my two hour study I demonstrated that all 10 participants experienced significant improvements in upright sitting posture when LifeChair was enabled. Overall a 68.1% increase in upright posture time was observed in these trials. The pressure heat maps for all 10 participants showed that LifeChair prevented rounded shoulders, improved overall posture symmetry and balance and reduced high pressure zones on the user's back. My 1-week trials presented fascinating insight into the behavioral aspect of sedentary workers through posture monitoring. The LifeChair trials in real offices was able to improve the overall sitting habits of all 10 users with improved posture habits being retained after LifeChair was disabled. The pilot studies have also demonstrated a breakthrough development in being able to sense the heart rate and respiration rate of the user from only contact with the LifeChair interface and the user's back. Non-invasive vitals information along with accurate real-time posture detection has paved the way for human condition classification such as stress, fatigue and relaxation. The LifeChair also seamlessly transitioned to be used for driver posture monitoring in a real car. During a free drive experiment, the LifeChair was able to successfully develop a relationship between driver posture and in-vehicle actions. The high sensitivity of the eTextile system could detect changes in driver steering wheel contact, turning the car and engaging with the pedal controls. The precise real-time posture monitoring can be used for driver fatigue prevention through safety and awareness alerts. This demonstrated LifeChair's vast capabilities and scalability and the successful development of an IoT platform to augment human posture coordination.

Through global business ventures, exhibitions and real-world trials – the LifeChair has been experienced by over a thousand people with positive reception. Its reach has extended beyond the labs and into corporate offices, automotive, rehabilitation and entertainment sectors. The proposed smart cushion has successfully been adopted as a posture augmentation device for improved wellbeing.

Thesis Summary Proposed Contents

Introduction

These days we spend more than 80% of our time sitting down. The daily condition of being sedentary is detrimental to our health as it opens opportunities for poor posture related health conditions. Slouching in particular, leads to muscular pain and injury, stress, fatigue, headaches, loss of focus and loss of productivity (Biswas, et al., 2015). On the other hand, good posture habits and upright posture have an abundance of positive health benefits including improved physical health, muscular pain prevention, heightened mood and productivity (Association, 1985).

In this research I have developed the LifeChair (Ishac K. &., 2018) (Ishac & Suzuki, 2016). It is a smart cushion for the back of the chair that uses our novel pressure sensing system, vibrotactile feedback and posture classifier to actively train sitting posture. It does this by detecting poor posture and sending haptic alerts to encourage the user to sit upright. By using unique vibration patterns, it communicates to the user spatial information, such as how to correct their posture. The LifeChair system can detect over 11 different sitting postures with an accuracy of 98.1% and has demonstrated effectiveness in increasing upright posture duration by 68.1%. The key component of the LifeChair is the design and implementation of the specially developed fabric pressure sensing array and our posture classification model. I designed and developed a conductive fabric-based pressure sensing technology that provides force sensitive output, can be used in large variables sizes and has demonstrated manufacturability and customizability. The LifeChair is also the only chair or cushion-based device capable of sensing the user’s heart rate and respiration rate from their back. In more recent studies, the LifeChair has also demonstrated wide capabilities for being used in detecting driver actions and status.

Related Works

There are many types of posture training devices, including (1) cushion types, (2) mobile types and (3) wearable types. In our research, we utilized a cushion type interface due to its non-invasive approach and functional capabilities. Other cushion type systems, such as Cushionware (Liang, Cao, Liu, & Han, 2014) and eCushion (Xu, Huang, Amini, He, & Sarrafzadeh, 2013), have attempted to detect sitting posture by using a pressure sensing pillow that the user sits on. These systems tend to move around as the user is sitting and are very basic indicators of good posture as they can only scan for simple pressure equilibrium or pressure along the spine. This does not guarantee good posture, as the user may still be experiencing the common rounded shoulders posture from mobile phone and electronic device overuse (Gold, et al., 2012) or the forward head posture (Cho, Kim, Yoon, & Choi, 2014) which are primary sources of sitting posture-based discomfort (Szeto, Straker, & Raine, 2002). Wearable systems, such as Waiston (Matsuda, Hasegaway, Arai, Arakawa, & Yasumoto, 2016), detect posture using a basic tilt sensor, yet this is not a good indicator of posture as it does not prevent rounded shoulders, the forward head problem and slouching to the sides.

Effective vibrotactile feedback as a communication cue on a human's back has been previously explored (Stronks, Parker, & Barnes, 2016). A challenging aspect is the size, location, power and distance between tactors. As outlined in this study (Stronks, Parker, & Barnes, 2015), the ideal spacing for lower back haptic acuity is 36 mm to 63 mm between motors. In the design of our spatial haptic feedback system, we used previous literature (Alahakone & Senanayake, 2009) as a foundation but experienced that there are many factors that can affect the feedback quality. This study (Zheng & Morrell, 2012) explored the affective reaction of haptic feedback as a positive or negative cue. It was demonstrated that haptic feedback as a negative cue more effectively generated a feedback response from the user.

System Design

In order to design the LifeChair system I considered several design criteria:

- Detects the user’s current posture with over 90% accuracy.
- Real-time active feedback about the user’s posture status.
- Thin profile to not cause discomfort or push the user off the edge of the chair.
- Soft and flexible to adapt to different chair shapes and sizes.
- Biomechanics based design to cater to various human body shapes and sizes.
- Portable to be able to easily carry and place on different chairs in daily life.
- Wireless to improve simplicity and reduce setup strain.

The base LifeChair material is composed of a breathable black 3D mesh fabric and PU leather that is detachable and hand washable. The LifeChair utilizes a double adjustable Velcro strap mechanism that is suitable for use with most office chairs as well as automotive seats.

Figure 1: LifeChair system overview

The LifeChair shape and size is designed based on anthropomorphic measurements of the 95th percentile US adult male and the 5th percentile Japanese adult female by considering parameters such as back height, shoulder width and seated shoulder height. Based on these parameters the cushion dimensions were set to 40cm width, 52cm height and 2.2cm thickness. The cushion was designed specifically to account for all critical posture regions on the user's back, including the shoulders, neck, upper back, middle back, lumbar regions and pelvic area. An important design consideration was the aspect of portability of the system to improve simplicity and ease setup. Most other devices are complex to setup, are often confined to a chair or require wired connections to operate. The LifeChair was designed to be lightweight, wireless and simple, so that it could easily be placed on most office chairs and be ready to use within a few seconds. The LifeChair is wireless and operates using a rechargeable 3.7V LiPo battery and communicates bi-directional data through BLE directly to a partnered smartphone application.

Figure 2: LifeChair Fabric Sensor System

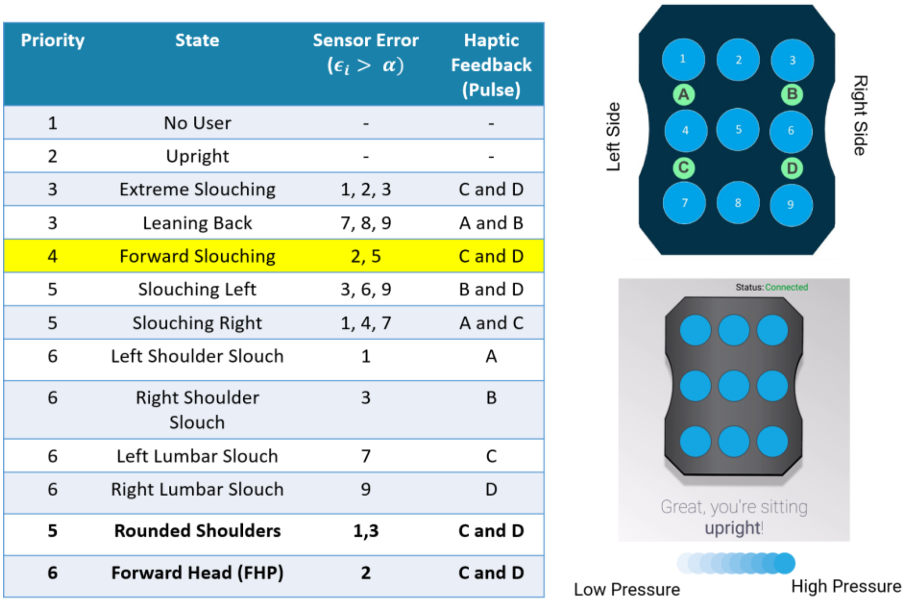
The most critical part of the mechatronics was the pressure sensing system. The only readily available technology was printed conductive material onto a PET plastic sheet. During initial trials we observed that large PET plastic sheets were not ideal for human interfacing during seating due to their rigidity, noise output when pressed and variations in resistance based on sensor distance to the pcb. We developed our own fabric sensing system that was composed of 2 copper weaved conductive fabric layers with a carbon filled conductive film layer in the middle. The top conductive fabric layer contained the 9 individual sensors with wires connecting to the PCB. The bottom layer was composed of a single sheet of conductive fabric that covered the surface area of the sensor array and behaved as the ground reference plane. The system was encased in an anti-bacterial black PVC cover.

In designing the haptics system of the LifeChair, we had to consider how many tactors would be needed in order to create various patterns that could be differentiated by the human back. Through pilot trials we had decided that 4 tactors would be used in total and be placed approximately to align with the upper left side, upper right side, lower left side and lower right side of the human back. Our pilot experiments aided in determining the appropriate horizontal and vertical separation between motors through simple haptics perception tests across 6 individuals. Based on these tests we positioned the motors with a horizontal distance of 22cm and the vertical distance between the motors was set to 17cm. The final selected actuators were DC coin-type motors C1234B016F mainly due to their high vibration G-force even while operating from a battery supply. The haptic feedback of each motor was tuned to vibrate in pulses. This is achieved by activating the motor with a PWM signal. Depending on customization options this is defined by an ON time t and an OFF time t which would combine to generate a pulse effect. In most standard cases of the LifeChair trials, the frequency was set at 4Hz or 250ms ON/OFF time.

The vitals sensing system was a major advancement in the development of the LifeChair interface. There has been little to no research in sensing the heart rate of the user from their back and no prior research has done so using a chair or cushion interface. Our sensing system utilizes a piezoresistive sensor that is attached to an amplifier and filter circuit and placed on the front face of the LifeChair cushion between the foam and the fabric cover. Even with a layer of 3D mesh over the sensor, we were able to detect the user's heart rate from only their back while sitting. Although the signal strength varied depending on the thickness of the clothes the user was wearing, in most cases a reading could be extracted and processed. We implemented a bandpass filter to only detect signals in the range of 40 BPM – 120 BPM which is the normal heart beat range of the human being while seated. After the bandpass filter we amplify the resultant signal to be more readable for further processing. The output signal can be used to estimate BPM and HRV.

Implementation

We developed a sitting posture classification algorithm that was based on real-time pressure data from our sensor array system. The posture classifier was designed based on human anthropomorphic dimensions and tested in a pilot study of 6 participants. It utilizes a threshold-based approach by taking as reference a calibration posture at time t is 0. This calibration reference is regarded as good or upright posture and is checked based on standard upright posture criterium in the field. These criterium for good posture include (1) vertical symmetry (2) pulled back and relaxed shoulder contact (3) lumbar contact (4) horizontal balance. Our calibration algorithm examines the sensor data to ensure it satisfies all 4 of these criteria before storing it as the calibration reference frame.



Priority	State	Sensor Error ($\epsilon_i > \alpha$)	Haptic Feedback (Pulse)
1	No User	-	-
2	Upright	-	-
3	Extreme Slouching	1, 2, 3	C and D
3	Leaning Back	7, 8, 9	A and B
4	Forward Slouching	2, 5	C and D
5	Slouching Left	3, 6, 9	B and D
5	Slouching Right	1, 4, 7	A and C
6	Left Shoulder Slouch	1	A
6	Right Shoulder Slouch	3	B
6	Left Lumbar Slouch	7	C
6	Right Lumbar Slouch	9	D
5	**Rounded Shoulders**	**1,3**	**C and D**
6	**Forward Head (FHP)**	**2**	**C and D**

Figure 3: Posture Classification System

The sensor values are voltages which are mapped to output pressure between 0 and 600 where 0 is no force and 600 is full force applied. Full force is considered 5kg and beyond, as after more than 5kg of force is applied the reading becomes saturated. The 9 sensor values are collected and sent simultaneously to the classifier which then compares the values to the calibration frame. The algorithm detects the absolute difference between each real time sensor value to its calibrated value. If the absolute difference is above a value alpha, then that sensor is deemed to have a posture error. The collective locations of sensor errors are then used to classify the user's current posture. The value of alpha is selected based on pilot studies and has been widely set to an integer value of 30. The list of postures classified, their sensor parameters and the provided feedback cue is detailed in Figure 3.

The LifeChair partners with the dedicated LifeChair smartphone app.

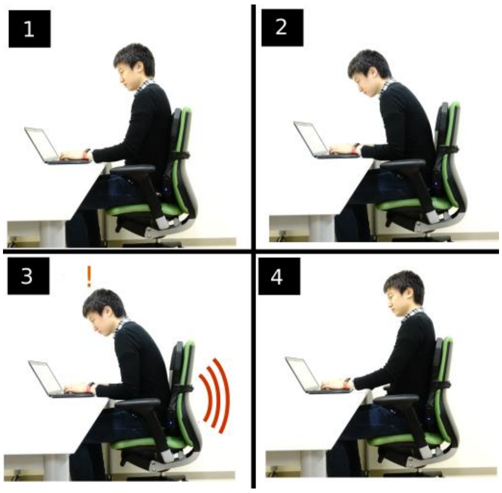


Figure 4: LifeChair system process overview

The project contains more than 600 individual files including 250 class files, 100 xml files and over 300 resource files. In total the app contains over 900,000 lines of programming. Internet connectivity is required for user account verification and synchronizing user statistics and preferences across multiple devices. Detailed user healthcare information is stored in a file on the smartphone and occasionally uploaded to the firebase. The firebase uses this data specifically for AI-generated healthcare reports for each individual user.

Experiments

Throughout this research we conducted various studies to evaluate core scientific parameters to human informatics and embodied interfaces. These studies focused on:

1) Feasibility verification of newly proposed technologies and designs.
2) Evaluation of the design, comfort and ergonomics of the embodied interfaces.
3) Evaluation of the effect of vibrotactile feedback and human response in different scenarios.
4) Analysis of human posture classification accuracy in different scenarios.
5) Analysis of human motion and behavior in different scenarios.

In chronological order the experiments conducted with brief results for each are as follows.

1) Pilot System Design: 6 person study to evaluate first prototype design.
    i. Haptics Design Study: Tested the vibration force, frequency, spacing, positioning and user response. Verified that the 4 quadrant motor positioning was effective. Spacing of 22cm horizontal and 17cm vertical allowed users to distinguish different vibration locations on the back.
    ii. Posture Classification Test: Analyzed the classification accuracy of the first 10 postures and demonstrated at 94% accuracy rate using the threshold method.
    iii. Vibrotactile Posture Performance Study: Showed that with vibration feedback, it was possible to positively shape the posture of all 6 participants.
2) System Upgrade Feasibility Tests: Developed new LifeChair based on pilot experiments and demonstrated its improvement compared to the first prototype.
    a. Smart Fabric Sensor Feasibility Study: Tested the functionality and piezoresistive properties of the fabric sensor. Demonstrated it was a more suitable solution.
    b. 20 Person Posture Classification Study: Observed that the posture classification accuracy with the new fabric sensors was higher than the previous study that used conventional sensors. Achieved 98.1% accuracy.
3) 10 Person Performance Study: Tested the improved system on 10 participants.
    a. Vibrotactile Performance Study: Further proved that vibrotactile feedback positively guided all participants towards an upright posture.
    b. User Interaction Survey: feedback demonstrated positive reception, especially towards comfort, functionality and design.
4) LifeChair Heart Rate Sensing Feasibility Study: Verifying the vitals extension of the LifeChair to prove heart rate can be detected.
    a. Detecting User Heart Rate: Demonstrated it is possible to detect heart rate from the user’s backside through the LifeChair device.
5) 2 person real world study: in-office LifeChair study at 3M and Rebel Sports HQ .
    a. Vibrotactile Performance Study: Showed that the day when LifeChair was activated, both users experienced significant improvements in posture.
    b. User Interaction Survey: Positive feedback around comfort, novelty and effectiveness – some haptics design improvements were requested such as a semi real-time mode and silent mode.
6) 10 person Long term study: Tested vibrotactile effect for a week in a secretarial office and lab based environment.

a. 3 Person Pilot Study: Prior to the test we proved the concept of an alternating days vibration ON/OFF experimental setup and also verified the potential positive effects of semi real-time vibration feedback in improving posture.
b. Semi Real-time Vibrotactile Performance Study: Results showed that all participants experience improvements in posture on the days when vibration was activated. Furthermore, good posture was retained on the final day when there was no vibration and was better than when the subjects began the study.
c. User Behavioural Study: We analyzed patterns in each users posture based on their job type.

7) Automotive Studies
a. Driver Posture Classification Study: LifeChair was able to classify all main postures in the car with close to 100% accuracy. It could also detect if the driver was making contact with the steering wheel or not.
b. Driver Action Study in 90 minute Free Drive: Successfully related driver actions such as turning the car, steering forward, accelerating and braking to LifeChair posture patterns.

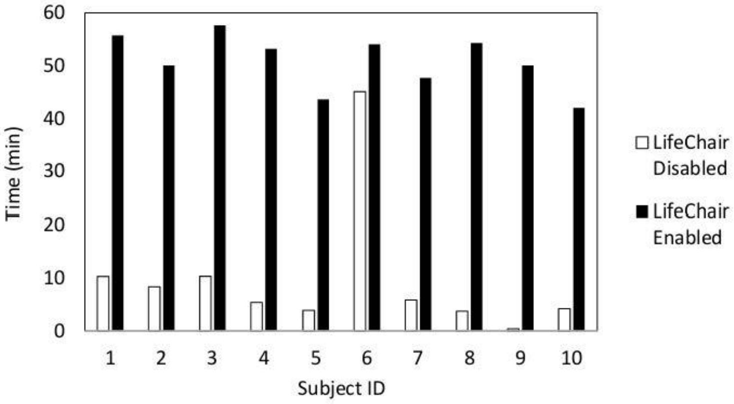


Figure 5: 10 person LifeChair performance study

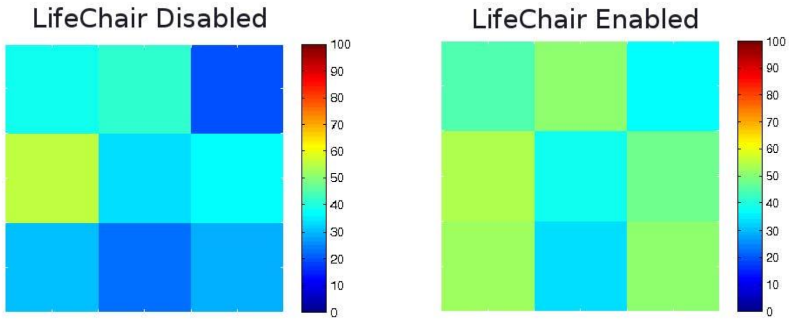


Figure 6: Average back pressure distribution across 10 subjects with and without LifeChair

Discussion

In regards to feasibility verification of newly proposed technologies and designs, the trend of results show clear improvements between consecutive prototypes. The switch to fabric based sensing from conventional FSR sensing, showed user approval in the survey as well as higher classification accuracy and increased upright sitting duration amongst all participants. This leads us to believe that the flexible and adaptive nature of etextiles is a better solution for embodied interfaces for human posture monitoring.

In relation to the interface ergonomics, throughout our experiments we maintained a human-centric design approach by constantly surveying the user's reception in each study. The haptic feedback module was upgraded to include a range of customizable parameters in the smart phone app to allow for personalized user experiences. By fine tuning the frequency and strength of the motors we observed an increase in upright posture duration as experiments progressed. As the LifeChair system was constantly refined based on user feedback and observations, we continuously tested the improvements it would provide on the user's upright posture. Between the first group of experiments, we clearly observed an increase to 68.1% in upright posture duration between the LifeChair models. As the LifeChair was tested in different scenarios, including real world offices and companies, it became evident that vibrotactile feedback was indeed effective in posture guiding, but required a minor level of personalization and customization between users to cater for individual preferences and changing workspace environments. As the research progressed, we were able to achieve higher classification accuracies between different users, reaching an accuracy of 98.1% using the threshold method. In latter stages of the research we extended the list of classifiable postures to include forward head posture and rounded shoulders posture, the 2 most detrimental and critical postures of todays technology filled world. Our heatmap results showed that we were successful in reducing both the negative effects of forward head posture and rounded shoulders amongst all 10 participants.

Future Works

Beyond this thesis, we are endeavoring to scale the LifeChair technology to multiple forms, implementable in real-world spaces. These include a chair-based version that embeds LifeChair technology, for a premium posture training experience. As well as a floor-based interface that will open new avenues assisted augmentation of human standing posture and motion.

Conclusion

In this research, we developed an embodied interface, named LifeChair, for posture correction that implemented our novel conductive fabric pressure sensor array and successfully improved the sitting posture of all participants. This system was also scaled to other embodied interfaces to demonstrate the vast sensing and augmentation range of the core LifeChair technology. As part of this research, we developed an adaptable, flexible, cost-effective and human compliant pressure sensing system for use especially in embedded complex interfaces, such as smart cushions and chairs. Our pressure sensors use a novel fabric-based layering method which is proposed as a full solution for manufacturing and real world use. The classification experiment demonstrated that the new LifeChair installed with the fabric sensing system could accurately classify 98.1% of all postures across 20 participants with significantly less variance than a flexible printed PCB system. After improving the system based on our initial findings, the performance study showed further improvement in posture correction by demonstrating a 68.1% increase in time spent seated upright when using the LifeChair which, in turn, reduced the overall time spent slouching. The automotive studies demonstrated the scalability of the LifeChair system to be used in the car. It established a clear relationship between driver actions such as steering and associated driver postures detected by the LifeChair. Our human-centric design approach allowed us deeper effective design into haptics feedback systems and interface ergonomics. Through constant analysis of user interaction and haptics we were able to produce an effective posture guidance system that the user positively responded to with minimal discomfort and disturbance. The combination of our extensive works in interface design, novel fabric sensing technology, vibrotactile feedback, detailed smartphone application and accurate posture classifier has successfully demonstrated augmentation and empowerment for human posture guidance and training. Preliminary studies also suggest that this system is capable of much more with the addition of human motion and behavioral classification and vitals sensing module. These systems will branch out the LifeChair to new fields of study in which it will continue to take on the everyday challenges of human life for the betterment of the human condition.

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