The Design of a Robotic Massage System for Lower Back Pain

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Massage is a conventional approach taken to relieve back pain. Due to cost, many people rely on massage chairs; however there are limitations on the effectiveness of massage chairs compared to human-driven massage or physiotherapy. This research paper explores the technical limitations of conventional massage chairs and seeks to overcome some of these challenges with the development of a massage robot. The proposed massage robot details the hardware and software design of the system. While pilot testing has anecdotally shown quality-of-life improvements in lower back pain from the use of the system, additional experimental testing of a larger subset of people needs to be completed to prove this system is more effective than traditional commercial massage chairs. Lastly, future technical implementations are discussed, including detailing on the use of artificial intelligence (AI) on collected data sets to improve the effectiveness and personalization of the massage provided by the proposed massage robot system.

Keywords: Massage Robots; AI integration with Massage Robots; Design of Massage Robot

Introduction

Nearly 619 million people globally are affected by back pain[1]. Due to the aging population, population increase, and widespread decrease of activity from the COVID-19 pandemic, these numbers are expected to increase, with an estimated 843 million people[2]. Massages have been thought to lead to various health improvements in both physical and mental aspects, including decreased joint pain and inflammation[3–5], as well as in increased relaxation[6,7]. While there is a lack of scientific evidence affirming the rea-soning behind the effectiveness of manual massage, there is empirical evidence that massage relies on biomechanical, physiological, neurological and psychological mechanisms[8].

Importantly, there is a variety of massage techniques that are deployed in Classic Western massages; two commonly practiced techniques are vibration and kneading[7,8]. Massage chairs seek to mimic massage techniques used by professionals and, therefore, tend to rely on different mechanisms to replicated and perform massage techniques seen by massage professionals. The vibration massage technique is most commonly created through vibrations typically deployed through masseuses' hands and fingers[9] or a handheld device[10] to create this vibration, which stimulates soft tissue and relaxes muscle tissues. The vibration massage technique is commonly seen in commercial massage chair. Under the surface of the chair, gears, and wheels rotate quickly to create vibration, seeking to relieve tense muscles[11]. The kneading massage technique is also frequently used by masseuses, to increase amounts pressure is small areas in the body, Kneading is highly regarded as the compression and muscular release is thought to increase blood flow and promote healing in soft tissue[9]. Mechanical massage chairs seek to replicate the kneading sensation by driving rollers in a small circular motion[11].

However there are still limitations in performance. Kim et al. has shown that while low-cost massage chairs are cost-effective, they are less effective when compared with physiotherapy[12]. Despite a gap in pain control outcomes, some customers prefer to use a massage chair than physiotherapy in aspects of cost, convenience, and availability. Massage chairs could supplement traditional physiotherapy as users can have access to the chairs in their own place and receive a massage on their own schedules. Although massage chairs do not have superior effectiveness, their results showed that the massage chair is a promising treatment for pain control and quality of life modification[12,13]. To address this, some massage robotic researches focus on manual massage treatment on humans, which is found to be different and more effective than other commercial massage chairs[14?]. To achieve these results, they address the combination of massage chairs and their effective manual massage, which would could have positive effects in relieving back pain.

To address some of the seen deficits in commercial massage technology, more advanced models are beginning to integrate artificial intelligence (AI) into their massage chairs to work towards personalization of massage while minimizing the effort required by a user to operate it. AI has been used to AI to detect users' skeletal structure, muscle shape, size, and condition which would help massage precision and effectiveness by performing personalized massages[15]. However, the integration of artificial intelligence in massage chairs is very limited. These advanced massage chairs are also highly expensive and unattainable for the majority of the population[15] and have limited data comparing the effectiveness of AI integrated massage chairs to either non-AI commercial massage chairs or massage therapists.

We hypothesize that current low cost massage chairs are not able to apply effective massage treatments to users due to the fundamental design constraint of integrating a mechanical massage system into a chair. This popular design of the massage chair system limits the ability for an affordable commercial massage system to effectively perform various effective massage techniques geared towards pain relief. Specifically, low-cost massage systems do not allow for personalization of treatment for different body types and sizes or allow for user input for treatment on discrete points on the body, which is necessary for addressing areas on the body that may be causing pain or discomfort. Therefore, two of the essential criteria identified for the design of a low-cost home massage and system are that it is both effective in relieving pain and is cost-effective as the prevalence of people with back pain is higher in lower socio-economic areas[1]. In this paper, the design of a massage robot is presented, developed specifically to address these shortcomings of current massage technology. Futhermore, future technological integration in home based massage systems are identified and discussed, specifically artificial intelligence, and how AI could assist in the global deployment and effectiveness of massage robots.

Methods

One major limitation of the massage chair comes from its basic design. The shape of the massage chairs can restrict the movement of the chair, which in turn limits the ability of the massage chair to be able to fully massage the entirety of the user. This leads to massage chairs providing massages that are minimally beneficial in contrast to traditional massage therapists. The current design of the massage robot presented in this work intends for users to lie in a prone position to receive a massage, more akin to a massage bed than a massage chair.

Methods

SketchUp, a 3D modeling software, was used to model the structure of the massage robot. This model, in Fig. 1, contains the design of the main body, base frame, placement of the motors, and other general, foundational aspects of the design. The main wooden structure contains an aluminum base frame, which contains linear slide motors that move the robot manipulator in any position within its three-dimensional workspace, as defined by the manipulator coordinate systems. 90-degree brackets were welded onto the main structure to the base frame to align and connect the design together. The base is a rectangular-shaped frame made out of aluminum rails. Four linear slide motors are placed at the edges of the frame. Six stepper motors are implemented in the design. Four motors are integrated into the base frame and the robot manipulator, which directly touches the patient's body.

Two motors are used to control the x-axis, which aligns with the user's spine, the y-axis, which aligns laterally across the user's back, and the z-axis, which controls the depth of the robotic manipulator. Each axis is independently controlled, enabling the movement of the robot manipulator to be highly flexible. The two other motors are used to adjust the plane of the base frame with respect to the main body of the robot, which minimizes the space required for storage, despite their high costs due to their precision and ability to control both position and speed, unlike cheaper DC motors and servo motors. The precise position is very important for this massage robot because it can directly affect a user's safety. When the motor's precision is low, it may rotate more than programmed, which could push the patient too firmly, harming the user. Furthermore, there is a switch at the end of each motor. The robot checks 30 times every second if it has reached the switch, meaning it has reached the end of the rail, for more accuracy and safety. Stepping motor control devices and Raspberry Pi computer devices are attached to the side of the main body. The robot hand is made out of plastic and shaped like a ball, and it is attached to an aluminum stick, which serves as a robot manipulator.

Load cells, which measure the force of pressure exerted on it, are attached at five sides of the robot arm. The robot can give pressure to the patient in various directions, left, right, forward, and backward, with respect to the user's spine, as well as depth into the back. The load cells are put in five different locations to measure pressure coming from all possible directions. A pressure limit is implemented within the software to prevent excessive pressure from being applied to the user. The depth of the robotic manipulator can reach a maximum of 20 pressure power, 20 pressure power was determined as an effective amount of pressure for massage usage, and the powers were tested on people. 30-pressure power was determined empirically to cause discomfort in users. The precision of load cell calculating pressure power is critical because too little pressure can result in insufficient forces exerted for an effective massage and too much pressure could potentially harm users' skin, muscles, or skeletal frame, increasing pain experienced by the user.

Operating system and Control Development

The developed code base for the massage robot integrates the control of the robot, generation of data sets for future personalization of massage, and user interfaces to the robot through a Graphical User Interface. A block diagram of the massage robot system is displayed in Fig. 2

The robot's operating system is Raspberry Pi, a series of small single-board computers. Raspberry Pi was selected for use in

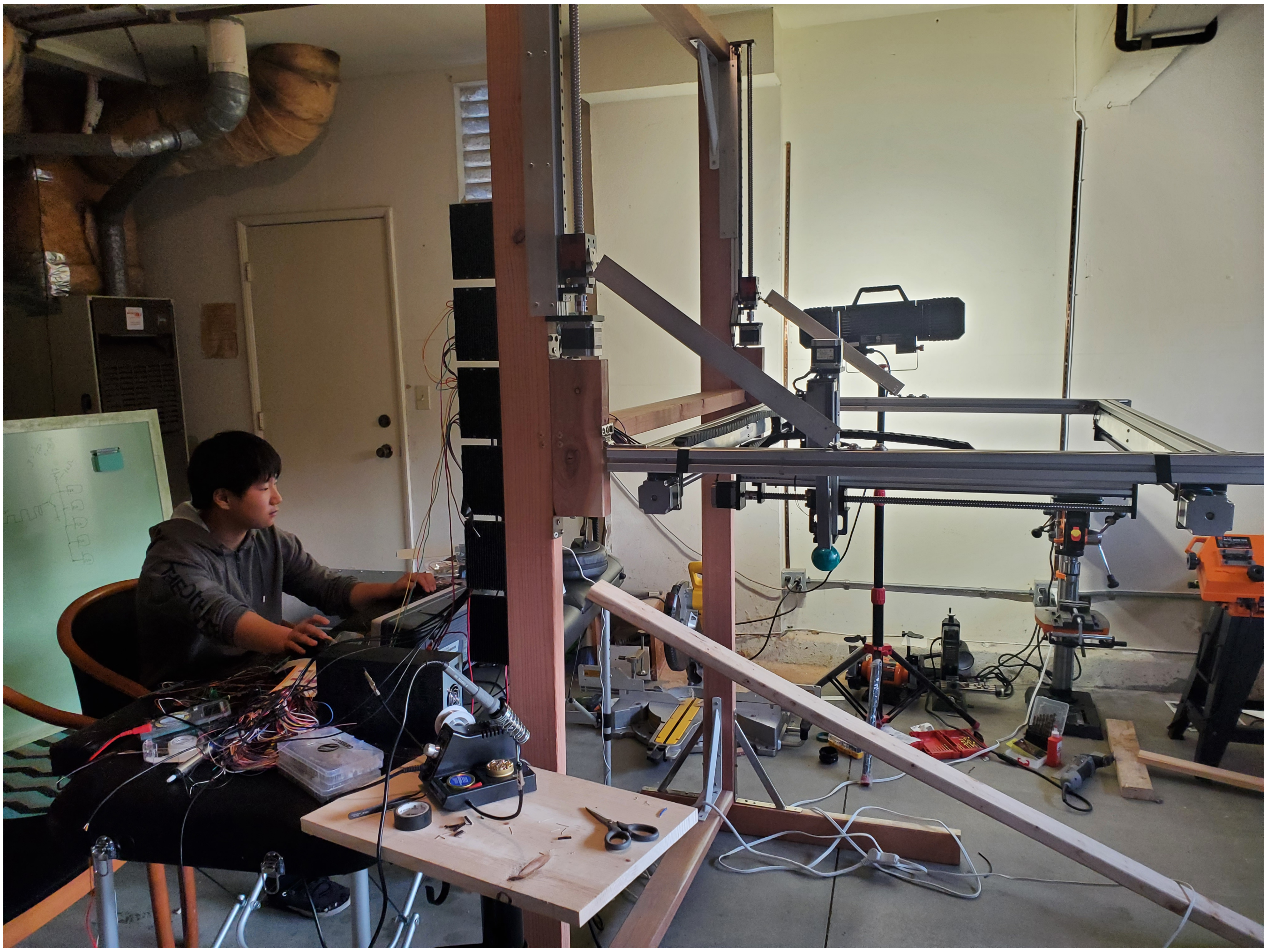

Fig. 1 Full design of the massage robot.

this development since it contains the baseline features required for development and relatively high computing speeds while still maintaining a low cost. Furthermore, Raspberry Pi supports Python code development; therefore, the robot is coded entirely in Python due to the supporting code bases available and sufficient computing speeds. While C-language runs faster when controlling hardware systems, the control of the massage robot does not require high-speed processing. Therefore, Python was sufficient to control the massage robot. Reliability is ensured by adding extra codes that recheck the input values. For example, when the user controls the massage robot with a controller joystick, the code checks the input value twice, not once, and if they match, it will proceed. Also, this step takes less than a millisecond, so that it would not bring a latency issue. Employing watchdog timers and redundancy in critical functions helps ensure reliability.

Two forms of massage, single-point pressure, akin to kneading, and vibration, were developed for this robot. As mentioned, precise control is possible because we used stepper motors to check and move in exact X and Y coordinates with respect to the spine.

Data collection

Data collection and storage is necessary for performing automated, personalized massages. User data is stored without any identifying information, and is labeled with a subject number known only to the user. This deidentified electronic data is stored on a password protected computer for data privacy and security. Data collection is limited to Cartesian coordinates, represented as 'x', 'y', and 'z', for massage points manually selected by the user. To enhance both storage and processing efficiency, the data is transformed into a string format. Adopting this approach would represent each data set as a string in the format "x;y;z," where 'x' corresponds to the x position value, 'y' corresponds to the y position value, and 'z' corresponds to the pressure power value. This compact representation not only minimizes storage requirements but also streamlines the processing pipeline. With this change, the system will process a single string argument per data set, as opposed to three distinct numerical values, resulting in reduced computational load and enhanced speed.

Moreover, transitioning to the proposed string format could lead to a more intuitive and user-friendly data representation. The values are concatenated with a semicolon separator, enabling a clear distinction between the x and y components of the data without the need for additional delimiters or identifiers. In summary, the idea of converting the saved massage points into a string format like "x;y;z" is a strategic choice for optimizing both data storage and processing efficiency. This adjustment will contribute to the more economical use of patient storage space and facilitate quicker data manipulation on the computer side, all while maintaining a coherent and intuitive representation of the massage points' coordinates.

Results and Discussion

Personalized Massage from the Presented Massage Robot System

This proposed design successfully allows for the personalization of the massage to the user. This is done in two ways: a manual massage function that allows for individuals to control the massage location and pressure, and an automated massage functions that tailors the massage to a person's individual body size and shape. Fig. 2 demonstrates the flow of information transfer of the robotic system.

For initial calibration, a camera takes a picture of the patient from above, capturing the user's body from head to foot. After taking a picture, the massage robot creates an outline in the picture along the patient's body to set up base measurement proportions. The computer traces lines along the patient by finding color differences between the patient and the massage bed, then calculates the distance between the furthest points along and across the spine. These values are compared to the standard proportional values of width and height, which is 360mm and 1740 mm respectively[16], identifying the proportions of the user to the standard model. This proportional data is applied to all massage techniques that would be performed on the data to ensure the massage robot is applied to the intended parts of the back.

The manual mode exists to allow the user to personalize the massage to address their specific needs. Specifically, this means patients can try different massage moves themselves to see what they prefer. This hands-on approach helps patients find the massage techniques that work best for them. This mode requires users to control the robot on their own, which may increase their cognitive burden, limiting the relaxation seen by the user. To address this, a user can save data about specific massage points, specifically depth and location on their body. Then, the robot can massage the same locations each time the robot is used, moving towards automated massages tailored towards the individual's preferences in the future. In the manual mode, the massage robot is controlled by the user. The user has access to a controller containing a joystick and two buttons. The planar location of the robot manipulator is controlled by the joystick. The pressure of the massage is adjusted through two buttons, which alters the robotic manipulator's position on the Z-axis. When the patient finds a massage point they may want to use in the future, they can save the data by clicking buttons on the computer screen and save the points for later automated massage. The camera takes a picture of the user and checks to see if their body reference has changed since the initial calibration then recalibrates this massage point to the current body position. Users can save a practically unlimited number of massage points, as

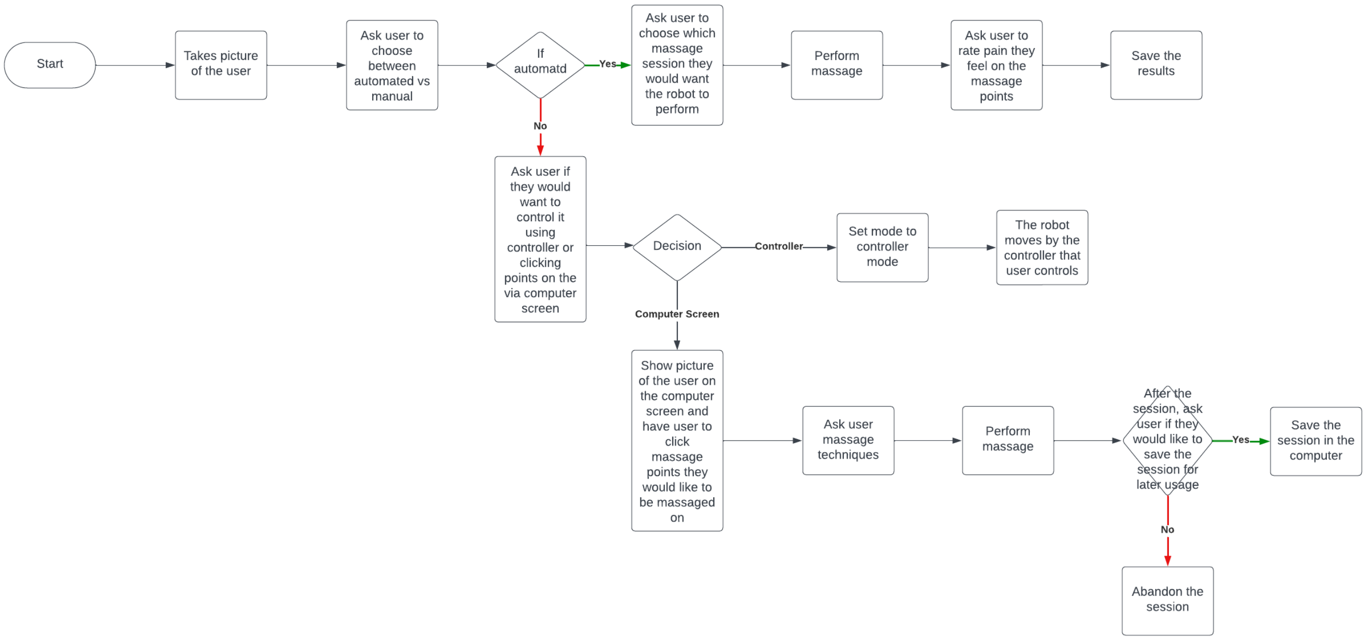

Fig. 2 Block Diagram of massage robot

Python allows for 536,870 massage sessions in a 32-bit system to be saved for any given user.

In the automated mode, the massage robot moves automatically to the pre-saved points that are from the users in their previous manual massage sessions. In initial testing, the automated mode was determined through testing users to be comfortable to use since it does not require users to manually control the robot, but the robot does not guarantee that it massages the exact points where the patient wants.

Analysis of Presented Massage Robot System

Initial testing has shown anecdotal physical benefits when compared to physical therapy or existing commercial massage chairs. Currently, the proposed robot lacks a user-friendly GUI and operating system; to increase system usability, there should be an additional focus on improving the interface between the system and the user.

Future development and testing will focus on the generalization of massage points across users. The goal of this generalization is to identify different massage techniques and ideal massage points that have been tested and enjoyed by many users. In order to work towards the development of a massage robot that automatically massages users in the most ideal locations without user input, a large, diverse sample size is required. The larger the data set collected, the more accurate the generalized samples the robot would have to learn from. Furthermore, it is important to note that these ideal massage techniques and location would be slightly different based off each user's body size. Hence, the calculation and adaptation of the massage points described are necessary to identify whether there are similarities in desired massage locations and pressures while using the robot. This focus on generalization could help cater to the diverse needs and preferences of many individuals, leading to personalized, effective, and well-rounded massages that suit a wide range of people. Another way to improve the proposed massage robot would be the integration of AI to the system. AI-integrated massage robots have great potential to improve therapeutic treatments. Current massage chairs with AI integration include voice recognition as well as facial and skeletal scans to heighten the personalization of massages to users[15]. However, while a few of these AI- integrated massage chairs are on the market, they are costly, and non-transparent about how their AI learns and adapts.

Before AI-integrated massage robotic systems are readily accepted by the general public, there are a few technical and ethical concerns that must be fundamentally addressed; specifically, regarding algorithmic transparency, effectiveness of the system, and system fallibility and safety. Transparency in how AI learns and adapts is critical to build trust with users and operators. One way this could be addressed is through human-computer interaction where the human user is informed with how a given massage robotic system makes decisions and have these choices be reinforced by human users. This could lead to the ability for massage robots to adapt massages to cater to various preferences and conditions while limiting unwanted bias from the system. The perceived increased effectiveness of the massages delivered is another key aspect concerning the acceptance of AI integrated massage robots. If AI-integrated massage robots are provided additional details about the user that non-AI-integrated massage robots are not privy to, AI-integrated massage robots could be trained to optimize and adapt massages to an individual, increasing the effectiveness of each massage. Lastly, safety features should be modeled into the hardware and software of robotic massage systems to limit fallibility of the system. Pressure and positional restrictions should be implemented to avoid failures from undesired learned behaviors.

Conclusion

A novel design of the massage robot has been developed and presented to address widespread back pain. The presented massage robot allows for the users to lie down on a bed, as opposed to the traditional massage chair, mimicking how individuals are oriented during traditional massages. The design used off the shelf components, including stepper motors, load cells, and a Raspberry PI, to control massage location and depth. Furthermore, the use of a camera allowed for the personalization of the massage to a user. This personalization is enhanced through the development of manual and automatic massage control modes. Lastly, this paper discusses how the collection of large data sets are critical generalization of massages across users and future integration of AI could heighten massage robot system performance.

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