Design of a Low-Cost, 3D Printed Upper Limb Exoskeleton for Stroke Rehabilitation

Analysis of the Time-Dependent Relationship between Pulse Oximetry and Society

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By
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On my honor as a university student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Health disparities disproportionately affect those of lower socioeconomic status, which refers to the combined effect of economic and social status on one's access to resources. Consequently, individuals of lower socioeconomic status experience poor health and a shorter life expectancy (Fiscella & Williams, 2004). Data has also revealed that racial and ethnic minorities are at higher risk for a "wide range of health conditions," such as "diabetes, hypertension, obesity, asthma, and heart diseases" compared to White individuals (Centers for Disease Control and Prevention, 2021). These health conditions include numerous risk factors for stroke. As a result, those of lower socioeconomic status and minorities experience a higher risk of stroke, a higher risk of a severe stroke, worse health outcomes as a result of stroke, and less accessible treatment (Lindmark et al., 2022).

In my technical design project, I propose the design of a new low-cost, 3D-printed exoskeleton to aid in stroke rehabilitation of the shoulder and elbow to be more affordable and, therefore, more accessible to those of lower socioeconomic status that are disproportionately at risk of experiencing a stroke. In addition to the technical project, I will investigate the evolving relationship between a common medical device, the pulse oximeter, and racial biases in society.

Analyzing the time-dependent relationship between the pulse oximeter and racial biases in society, as well as designing a new low-cost**,** upper limb exoskeleton, will provide a more comprehensive and holistic, and thus more effective, approach to addressing racial bias that has embedded itself into the healthcare system. Because the issue of racial bias embedded into the healthcare system, and, therefore, medical devices, is socio-technical in nature, it requires attention to both its technical and social aspects. In the following, I elaborate on a technical project that functions to develop a stroke rehabilitation device that is more accessible to those at higher risk of stroke and an STS project that examines how the design of the pulse oximeter is influenced by societal factors, specifically racial biases, over time.

Technical Project Proposal

Stroke is a leading cause of death and disability worldwide (Donnan et al., 2008, p. 1612). Consequently, stroke survivors require prolonged rehabilitative physical therapy, typically one-on-one with a therapist, which is generally costly, time-consuming, and labor-intensive (Wu et al., 2016, p. 1). In contrast to manual manipulation by physical therapists, wearable robotics, also referred to as exoskeletons, have been designed to provide assistive and rehabilitative technologies for decades. Upper limb exoskeletons enhance the mobility of upper limbs and, therefore, improve the stroke survivor's ability to manipulate their environment which is "crucial to patients' independence, self-esteem, and quality of life" (Ochieze et al., n.d., p. 1). The most common upper limb rehabilitation exercises include "shoulder abduction/adduction, shoulder flexion/extension, shoulder internal/external rotation, and elbow flexion/extension" (Chen et al., 2020, p. 2). Thus, exoskeletons with those four degrees of freedom, or four axes of motion, would be advantageous for stroke survivors and physical therapists to utilize in the stroke rehabilitation process. To enact these four degrees of freedom, an actuator, the component of a device that enacts physical movement, would be needed. A common actuator used in exoskeletons is the pneumatic artificial muscle. The artificial muscle is a "braided pneumatic actuator composed of an inner rubber tube wrapped in a layer of nonexpendable double-helix-braided shell." As the rubber tube is filled with air, the artificial muscle contracts longitudinally to the inflated volume to create a pulling force that actuates the robotic exoskeleton (Chen et al., 2020, p. 2). The magnitude of the pulling force exerted by the pneumatic artificial muscle is dependent on the airflow into it. The airflow into the pneumatic artificial muscle will be regulated by the orientation of the upper limb, sensed by inertial measurement units (IMUs) placed on the upper shoulder and the top of the forearm, and by the electrical signals emitted by muscle motion, detected by electromyography (EMG) sensors placed on active muscles. The actuator and the sensors will be attached to the upper limb through a mechanical and textile design that consists of 3D-printed structures, an arm brace with adjustable velcro straps, and other components.

A current stroke rehabilitation design similar to my proposal is a four-degree-of-freedom "cable-driven upper limb robotic exoskeleton…actuated by pneumatic artificial muscle actuators". This design is intended to be compact and lightweight while also molding to the user's anatomical structure and matching the motion of the shoulder and elbow as closely as possible (Chen et al., 2020, p. 2). However, this design utilizes components that may be moderately expensive and, as a result, the design may not be as widely manufacturable or accessible to those disproportionately at risk of stroke. Therefore, the proposed design will consist of low-cost components, such as 3D-printed structures and open-source software, that maintain rehabilitation quality and minimize the overall cost of the exoskeleton. Without the design of a low-cost, easily manufacturable exoskeleton, many stroke survivors will not have easy access to an effective stroke rehabilitation device.

This technical project aims to design a four-degree-of-freedom upper limb exoskeleton integrating pneumatic artificial muscles to actuate movement, IMU and EMG as sensors, and a mechanical design consisting of 3D-printed and textile components. The previous design of the cable-driven upper limb exoskeleton discussed before will serve as the basis for a new, upscaled design that incorporates lower-cost materials and is easily manufacturable.

Design data will be obtained from sources such as articles detailing alternative four degree-of-freedom designs that incorporate a pneumatic artificial muscle, the usage of IMUs and EMGs in exoskeletons, numerous upper limb exoskeleton testing methodologies, and research papers discussing various exoskeleton mechanical designs. The design data will be incorporated into a dynamic model of the four-degree-of-freedom exoskeleton. The proposed project will be completed as a team of seven students over the course of two semesters in MAE 4610 and MAE 4620. The development of the mechanical design, CAD model, mechatronic system, and testing simulations will be divided equally among the team members.

STS Project Proposal

Pulse oximetry is a painless, noninvasive method to measure blood oxygen saturation that can be used at home, in surgery, during doctor appointments, and in various other settings. Pulse oximetry is most commonly used to quickly assess a patient's health or to monitor the blood oxygen saturation of patients at risk of low blood oxygen levels due to lung and heart disorders. To determine blood oxygen saturation, the pulse oximeter is clipped onto a patient's fingertip and emits light that passes through the finger. The amount of light not absorbed by the tissue or blood while passing through the finger is detected by a sensor on the other side (Yale Medicine, 2021). Using calibration data previously acquired from healthy volunteers and the data collected by the sensor, the device calculates the patient's blood oxygen saturation (Open Critical Care, n.d.). It is important to monitor blood oxygen saturation levels, especially in patients at risk of low blood oxygen levels, because a blood oxygen level of less than 92% indicates that tissues in the body may not be receiving enough oxygen and a level of less than 88% may indicate that a patient is in critical condition (Yale Medicine, 2021). Occult hypoxemia is a condition characterized by blood oxygen saturation of less than 88%, despite a pulse oximeter measurement between 92% and 96%. Thus, patients with occult hypoxemia may receive delayed medical care when they are in critical condition. A 2020 study at the University of Michigan found that Black patients experienced occult hypoxemia almost three times more frequently than White patients (Sjoding et. al., 2020, p. 2477-2488). Furthermore, the method of calculating blood oxygen saturation based on the passage of light through the patient's skin, the usage of calibration data that is likely biased towards those of lighter skin, and how pulse oximetry is known to be less accurate for those of darker skin indicates that racial bias has been integrated into the design of the pulse oximeter (Yale Medicine, 2021).

It may appear that the pulse oximeter was designed with racial bias integrated into the calculation of blood oxygen saturation and always has been. However, an early pulse oximeter design developed by Hewlett-Packard in the 1970s was created for use in the healthcare system to measure blood oxygen saturation using a racially and ethnically unbiased method due to the societal pressures placed on Hewlett-Packard following the Civil Rights Movement, the movement that fought for the equality of Black Americans and other people of color in the United States (Anti-Defamation League, 2022; Merrick & Hayes, 1976, p. 4). If we continue to think that the pulse oximeter always had racial biases incorporated into its design, then we will not understand how its role and influence in society, specifically in the healthcare system, have evolved over time.

I argue that although the pulse oximeter was designed to determine a patient's blood oxygen saturation in a racially unbiased manner, over time pulse oximetry gained momentum, becoming routinely used in healthcare to the extent that efficiency was prioritized over reducing inaccuracies due to skin pigmentation, ultimately shaping the healthcare system with racial bias integrated into the treatment of health conditions characterized by low blood oxygen saturation. Technological momentum can be thought of as the time-dependent relationship between the concepts of technological determinism and the social construction of technology. Technological determinism refers to the belief that technical artifacts, such as physical objects or software, shape society. In contrast, the social construction of technology is the belief that the development and usage of technology are shaped by society (Hughes, 1987, p. 141-142). Technological systems are initially constructed by society, however, as the system gains momentum and societal influence, these systems become less shaped by society and begin to shape it. Therefore, as technological systems gain momentum and influence, they shift from the social constructivist model towards the technological determinist model (Hughes, 1987, p. 148-149). Applying the concept of technological momentum, I will describe how pulse oximetry gained momentum over time, becoming less shaped by society and increasingly beginning to shape it. To undertake this analysis, I will utilize evidence from recent medical studies that quantify the health consequences of inaccurate pulse oximetry readings and the impact of these biases on the quality of medical care racial and ethnic minorities receive.

Conclusion

The deliverable for the technical problem discussed in this paper will be a full design of a low-cost, 3D-printed, upper-limb, stroke rehabilitation exoskeleton capable of providing motion consisting of four degrees of freedom: three at the shoulder and one at the elbow. The STS research paper will strive to define the evolving relationship between the pulse oximeter design and racial biases embedded in society. This will be accomplished by applying the concept of technological momentum to fully characterize the time-dependent shift of the pulse oximeter design from the social construction model to the technological determinism model. The combined results of this technical report will serve to address the issue of racial and ethnic health disparities in medical devices and health outcomes from a sociotechnical lens, highlighting key considerations for the future of ethical health care and proposing the adoption of a more accessible, low-cost stroke rehabilitation device.

Word Count: 1857

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