Robotic Rat Hindlimb Model for Neuromuscular Regeneration and Rehabilitation of Volumetric Muscle Loss Resulting from Polytrauma

Investigating How the Development of Increasingly Advanced Medical Devices Further Segregates Global Access to Health Technology Solutions

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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

The technical component of this research project is focused on the development of a robotic rat hindlimb, concentrated on the ankle and foot, to create a physical model for the evaluation of functional recovery from volumetric muscle loss (VML). Following VML injury, resident cells and structures primarily responsible for regeneration are lost along with the intrinsic muscle regenerative process, leading to long-term functional impairment and disability (Aguilar, et al., 2018). While several different approaches have been explored to treat patients with such injuries, all current therapies are limited in their ability to fully restore muscle function. The Motor Analysis and Motor Performance Laboratory at the University of Virginia, directed by Dr. Shawn Russell, is investigating these limitations by developing computational movement analysis modes of Lewis Rats. The model being designed on the technical side of this project will act as a steppingstone between Dr. Russell's current computational models and future animal testing with the aim of improving functional muscle recovery gained through current novel regenerative therapeutics for VML injuries.

The sociotechnical component of this project covers how the development of increasingly advanced medical devices further segregates access to health technology solutions. While these advancements in medical technology help revolutionize the industry and the patient treatment landscape, they also highlight growing barriers that limit their reach to low-income populations and underserved communities. High costs associated with cutting-edge medical devices, limited insurance coverage, and uneven distribution of resources create significant hurdles in obtaining access. A study on the economic burden of health inequalities run by the Joint Center for Political and Economic Studies and Johns Hopkins University found that the elimination of these inequalities for minorities would reduce total costs by approximately $1.5 trillion over a 3-year period (Riley, 2012). Furthermore, the complexity and regulatory requirements for these devices contribute to their exclusivity, often leading to higher concentrations in well-funded, urban environments. This segregation in healthcare access drives health disparities even further as patients in marginalized communities are less likely to interact with such solutions, affecting their overall quality of life. Addressing these disparities requires an emphasis on affordability and accessibility throughout the development process of new technological innovations in the medical sector so that such creations can benefit all individuals equally.

The technical and sociotechnical aspects of this project are aligned as the advancements being made in obtaining functional muscle recovery following VML injuries are such innovations that require immense resources, hence driving disparities in access to healthcare solutions. Together, these two aspects highlight how to explore potential medical advancements to enhance patient care while considering the need to make these technologies affordable and accessible for all, ensuring equitable health outcomes across diverse populations.

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With approximately 4.5 million reconstructive surgical procedures performed annually because of VML injuries, the need for an effective approach to direct skeletal muscle regeneration is profound (Grasman, et al., 2015). Current methods to treat VML include surgical intervention, physical therapy, acupuncture, and biological scaffolds. Surgical techniques are often centered around autologous muscle grafts which lead to donor site morbidity, inadequate nerve connections, and high rates of failure overall. While physical therapy and acupuncture can help counteract muscle atrophy, neither is capable of generating entirely new muscle. Biological scaffolds have been shown to support tissue structure and promote muscle regeneration;

however, they have a high associated risk of negative immune responses and infections (Liu, et al., 2018).

In order to develop new treatment methods for VML injuries that address the full scope of muscle functionality loss without the correlating limitations or risks, numerous studies need to be conducted to evaluate true effectiveness. While computational models are capable of computing large amounts of data at a significantly increased speed with easily manipulated variables, there is no way to ensure a direct translation of its results into live animal testing due to a variety of environmental factors. This creates the need for a physical model to test computational hypotheses before transitioning into animal testing. Current models of skeletal muscle structure are limited in their ability to build off computational models since they are often over simplified and fail to replicate the full scope of muscular interactions. To develop a model that is a strong enough replication of true anatomical structures and functions, and capable of deriving relevant data, it needs to extend beyond only including skeletal muscle tissue. Embracing the findings of related research fields such as motor-unit recruitment principles, muscle fiber type distributions, the mechanical behavior of adjacent tissue, and the existing dynamics within the musculoskeletal system are crucial to achieve impactful results. (Röhrle, et al., 2012).

To support the Russell lab in its journey towards developing innovative strategies for neuromuscular regeneration and rehabilitation of VML injuries resulting from polytrauma, the technical component of this project seeks to design a model that accurately mimics all muscular interactions and capabilities present in a live Lewis Rat. Extensive research surrounding the anatomy of the Lewis Rat hindlimb will drive which materials and types of interactions are present in this model with a focus on loading capacity and elasticity. A key consideration when developing this model will be the combination of both active and passive muscular movement. The passive movement of foot muscles, particularly those supporting the arch, plays a pivotal role in absorbing and releasing energy during normal walking motion. Incorporating these passive elements is essential for accurately modeling foot mechanics as they account for the foot's resilience and stability throughout loading (Kelly, et al., 2018). The anatomical accuracy of this model will be validated through a comparison with previous Lewis Rat data that was used to develop the initial computational models in the Russell lab. Motion capture cameras will be used to collect data for this validation with tracking markers placed at key anatomical locations along with an evaluation of ground reaction forces generated during normal walking motion.

To evaluate natural compensation tendencies following VML injuries as well as the effectiveness of novel regeneration treatments, this model will incorporate actuators to control muscle motor function. These actuators will have the ability to both recreate muscular activity during normal movement as well as deactivate entirely to mimic a VML injury. An evaluation of gait patterns before and after a simulated VML injury will provide invaluable insight into key areas to target to improve overall functional muscle recovery achieved through newly developed neuromuscular rehabilitation and regeneration techniques.

Investigating How the Development of Increasingly Advanced Medical Devices Further Segregates Global Access to Health Technology Solutions

Within the sociotechnical component of this research project, disparities in treatment accessibility for VML injuries are being investigated to discover how advancements in VML treatments might create unequal access to care for marginalized populations. This is important because it highlights the responsibility of innovators to go beyond designing scientific breakthroughs and ensure universal access, regardless of economic and social status. While novel treatments for VML injuries hold the promise of greatly enhancing the quality of life for injured veterans, their development demands substantial resources and funding which often leads to unequal distribution of access.

Developing treatments for VML injuries is just one example of advanced medical device technology that is reshaping healthcare, all of which offering groundbreaking diagnostic and therapeutic solutions. Yet, these innovations often deepen global disparities in access to health technology. Cutting-edge devices are costly, requiring both highly skilled personnel and high-tech infrastructure, which are often limited to wealthier regions. This gap creates significant barriers for low-resource communities. In a study conducted to investigate disparities in health care, it was found that minorities often face significantly greater personal challenges in accessing health care such as getting time off work to visit a doctor, leading to individuals forgoing medical evaluation, preventative care, and even treatment (SteelFisher, 2004). As the evolving technological landscape surges forward, new platforms such as telehealth that advertise improved access and care only deepen these disparities as they are misleading in their requirements. These health information technologies require adequate internet access, compatible devices, a strong sense of health and digital literacy, and access to private spaces for discussion with health care professionals (Saeed & Masters, 2021). Without addressing these barriers, global health inequalities will continue to severely impact poorly represented and marginalized communities through the ongoing advancement of medical devices, systems, and treatments.

The segregation of global access to health technology solutions will be primarily analyzed through the justice evaluative technique supplemented by case comparisons. Within the justice evaluative technique, implementing a distributive analysis will provide insight as to how access to medical devices and technology is distributed among various social groups. This investigation will determine whether certain groups such as low-income or marginalized populations are systematically excluded from obtaining care and what underlying factors are driving these disparities. The devotion of healthcare resources will act as a strong guideline for this evaluation with trends such as how populations and investments are transitioning outward from central city locations, leaving central city residents, particularly those with lower incomes, with a problematic and highly unequal landscape of healthcare providers (Hawthorne & Kwan, 2013). Policy reports, healthcare utilization data, and patient interviews will be incorporated as sources to prove the existence and prevalence of these disparities. This evidence will be interpreted by identifying patterns of exclusion in access, highlighting how novel treatment techniques fail to implement equal distributive systems and worsen healthcare inequalities.

Building on the distributive justice analysis, case comparisons will examine instances in which treatments such as regenerative therapy for VML injuries have been developed and distributed amongst varying populations. This evaluation will focus on variations in accessibility across different socioeconomic groups with an emphasis on how technological development shifts this accessibility. Evidence for this comparison will include device availability, pricing, insurance coverage, and patient demographics, all available via various healthcare systems public data. A key component of these case comparisons will be to incorporate the most up-to-data data as the medical technology field is rapidly evolving with additional environmental and economic factors impacting its future with each new year. For example, while the affordable care act and policy changes during COVID-19 boosted overall insurance coverage in the U.S., the unwinding of the pandemic-era policies will lead to an increased uninsured population. In addition to this uninsured population, a large percentage of U.S. residents that maintain some form of health insurance still face high deductibles and other cost sharing that often lead to delayed treatment and negative health effects (Radley, et al., 2024).

Conclusion

To summarize, this research project is divided into two key focuses: the technical component and the sociotechnical question. Regarding the technical component, this project aims to design a robotic rat hindlimb model to enhance research for neuromuscular regeneration and rehabilitation of VML resulting from polytrauma. This model will act as a transition study between current computational models and future animal tests with the ability to recreate gait shifts following a simulated VML injury and provide insight into increased functional muscle recovery. The sociotechnical research question for this project investigates how advancements in VML treatments might create unequal access to care for marginalized populations.

The deliverables from this project have the potential to significantly advance both medical research and societal equity in healthcare access. Upon successful design of the robotic rat hindlimb, Dr. Russell and his fellow researchers will be able to thoroughly assess the effectiveness of regenerative treatments in improving muscle function following VML injuries as well as explore new techniques to improve such treatments. In a broader scope, this technical design project will facilitate a more precise understanding of the muscle recovery process and an enhanced track for developing novel therapies that reduce long-term functional impairments. The sociotechnical research tied to this project highlights the immense impact of health disparities and emphasizes the need to make accessibility a core component of technological development in the medical space. The finalization of this research will shine a light on the driving factors behind these disparities and offer impactful approaches to addressing these issues.

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