How wearable sensing can be used to monitor patient recovery following ACL reconstruction

Investigating the Implementation of Automated Technology in the Healthcare Industry

A Thesis Prospectus

In STS 4500

Presented to

The Faculty of the

School of Engineering and Applied Science

University of Virginia

In Partial Fulfillment of the Requirements for the Degree

Bachelor of Science in Systems Engineering

By

Kevin Cox

November 1, 2021

Technical Team Members:

Jon Saksvig, Alice Warner, Drew Hamrock, Jane Romness, Sydney Lawrence, and Sean Lynch

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.

Kevin Cox

ADVISORS

Rider Foley, Department of Engineering and Society

Mehdi Boukhechba, Department of Engineering Systems and Environment

Introduction

In the United States alone, approximately 150,000 anterior cruciate ligament (ACL) injuries occur every year, translating to over $500 million in healthcare costs (Coleman, 2019). These injuries can be especially detrimental to younger athletes, who have to endure not only a 6-9 month recovery and rehabilitation period, but also encounter an increased risk of reinjuring their ACL once they return to competitive sports. One study reported that athletes who were less than 20 at the time of an initial ACL surgery had a subsequent reinjury rate of 28%, approximately six times higher than that of athletes who have not torn their ACL before (Webster et. al., 2014).

A major determinant of the likelihood of reinjury is the rehabilitation process after the initial surgery following an ACL injury. During rehabilitation, patients work with physicians to gradually advance toward walking, running, and eventually playing high-impact sports again. However, each recovery process is unique to the patient and circumstances of the injury, and an incomplete/improper rehabilitation may lead to greater risk of injury (Nyland et. al., 2010). This capstone project will aim to improve the ACL reconstruction rehabilitation process by using wearable sensors to monitor the recovery of patients in the months following surgery.

With the goal of attempting to utilize mobile sensors and machine learning algorithms to aid in the traditional rehabilitation process, this project serves as one example of the increased integration of new technology and automation into the healthcare industry, which have been two of the main drivers in recent changes in the medical industry (Thimbleby, 2013). Introducing new technology into the existing system of infrastructure and workforce creates many opportunities for increased efficiency and improved care for patients, but also can pose some

issues in terms of security, privacy, and disruptions of the current healthcare system (Lustgarten et. al., 2020). The advancements offered by automation technology must be coupled with a careful analysis of its implications toward social groups, existing technology, and infrastructure before being fully adopted. This capstone project, which involves utilizing remote sensors to collect and analyze metrics indicative of successful ACL reconstruction rehabilitation, provides one specific context for investigation into how the increased integration of automated technologies in the healthcare industry interacts with the existing standards of practice and roles of physicians.

Utilizing Remote Sensors in ACL Reconstruction Rehabilitation

Currently, the post-ACL reconstruction rehabilitation process consists of 6-9 months of regular sessions of physical therapy with a rehabilitation physician. These sessions gradually increase in rigor and involvement until the patient is cleared to resume walking, running, and eventually returning to their regular daily routine and sports activities (Myer et. al., 2006). Typically, the final decision from a physician to clear an athlete to return to sports is made based on quadricep muscle strength and performance on jumping exercises (Menzer et al., 2017). However, this decision process usually does not consider the potential risk for ACL reinjury (Losciale et. al., 2019). Additionally, most of the determinants of quadricep strength and jumping ability require high-impact activities, which can only be done in the later stages of rehabilitation. There exists a clear need for precise, constant, and objective analysis of the condition of patients' rehabilitation process in order to ensure a successful recovery and minimize the risk of reinjury.

This project will be conducted in two main phases. In the first, patients who have recently undergone ACL reconstructive surgery will wear Trigno Avanti sensors (seen in Figure 1) during their regular physical therapy sessions. These sensors will provide accelerometer and electromyographic (EMG) data while the patient conducts basic activities such as walking, extending and retracting their legs, and jumping. Simultaneously, healthy participants will also conduct the activities wearing the same sensors. Following data collection of 10 patients and 10 healthy participants, the second phase will begin. This will involve analyzing the accelerometer and EMG data provided by the sensors to highlight features indicative of differences between the two groups of participants. Some potential features include the level of symmetry between steps when walking, the acceleration of a participant's legs while extending and retracting, and differences in impact force when jumping off of each leg. Previous studies have utilized similar sensors in monitoring the effects of ACL surgery on attributes such as gait, which may have an effect on how a patient's body develops after surgery and the potential for reinjury (Gurchiek et. al., 2019). Following the analysis of data and extraction of specific features that differentiate between a patient and a healthy participant, a predictive model will be developed with the intended goal of distinguishing between these two groups of participants based on their accelerometer and EMG data. Recent research has trended in the direction of machine learning models, attempting to predict the efficacy and progression of rehabilitation through these predictive models (Tedesco et. al, 2020). Compounding the constant monitoring of key features such as gait and quadricep muscle symmetry with an accurate predictive model will aid rehabilitation physicians in conducting an efficient, successful rehabilitation process while limiting the risk of reinjury.

Figure 1: Trigno Avanti Sensors on a Participants Lower Limbs. Source: Boukhechba (2020)

The long term goal of this project is to allow for patients to wear sensors in their day-to-day lives during rehabilitation. With metrics indicative of ACL patients vs healthy participants and a model that can successfully predict whether a patient is progressing properly in the rehabilitation process, patients can be more accurately diagnosed and treatment can be tailored to an optimal process. Similar models developed have already shown an accuracy over 80% in predicting asymmetrical knee power, one of the key indicators in the outcome of a rehabilitation process (Pratt et. al., 2018). The goal, however, is not to completely phase out rehabilitation physicians, as evidence has shown the importance of the physical presence of professionals during this process. In one study, researchers separated patients in the rehabilitation

process of ACL reconstruction into two groups: one supervised by rehabilitation physicians and one unsupervised. Although the two groups conducted the same exercises during their process, the supervised group had a much more effective process in terms of decreased pain and an increased day-to-day quality of life (Saxena et. al., 2020). There must be a balance between these automated technologies and the physicians that traditionally work with patients. This interaction between new technologies and physicians is seen across the healthcare industry, and is the primary focus of the next section.

Socio-technical Aspects of Automation Technologies in the Healthcare Industry

Throughout this study, rehabilitation physicians will be in their usual role of guiding patients through the post-surgery rehabilitation process, but now with the added component of sensors constantly collecting data. This new technology and its associated designated exercises, while having the intention to improve the process of rehabilitation, may alter the standard practices of rehabilitation physicians. If the project is successful in utilizing the sensors to improve the rehabilitation process, some disruptions regarding how the use of this technology may affect current practices in this industry may be encountered. Rehabilitation facility administrators may consider altering standards of practice, physicians may see their roles as primary decision makers change, patients may experience a new technologically-driven method of therapy, and manufacturers of sensors may tailor designs for rehabilitation purposes. Previous research has shown that introducing more automation into the healthcare industry affects not just the technological aspect of medical facilities, but also broader organizational aspects within personnel and management of physicians, stressing the importance of considering the extensive effects of introducing these new technologies (Benzidia et. al., 2018). This project serves as one

of many avenues that technology and automation are potentially being implemented in the healthcare industry. Already, remote sensors and predictive models are being utilized for a multitude of uses, such as in-home rehabilitation and remote care for elderly patients (Ho et. al., 2019). While the increased use of automation technology may allow for more opportunities in data collection and increase the accuracy of diagnoses and treatments, careful consideration and analysis is needed before attempting to shift the healthcare industry completely toward automation.

Previous research has delved into some of the potential issues that the increased integration of technology into healthcare presents. Some have focused on privacy-related risks of having a high-technology medical system with the use of specific case studies, such as the WannaCry malware incident, which affected 80 NHS trusts and more than 600 different National Health Service (NHS) organizations in England (Meinert et. al., 2018). While strict laws and regulations exist with the intention of keeping all patient data secure, this specific malware attack provides just one example of a breach in security and privacy. Computer use, patient care, and even medical equipment were all hindered by this breach. Although the adoption of technology presents many opportunities for benefit, it also introduces new forms of security and privacy risks. Beyond privacy and security, integrating technology into the healthcare system also introduces concerns of unsustainability and issues with scalability. Although a technology may be cutting-edge at the time of its introduction, it may already be outdated and replaced with more optimal solutions by the time it would be able to be fully integrated and scaled up into broader systems (Meinert et. al., 2018). Outside of these, the financial implications of increasing the use of technology in healthcare must be considered. With the cost of healthcare, specifically in the United States, already rising to amounts unaffordable to many average citizens (Crowley et al.,

2020), adding more high-cost technology may make this problem even worse. Although more advanced technology and automation will increase the abilities of healthcare providers, it will likely correspond with an increase in healthcare costs which may not be fully justified by these advancements (Kumar, 2011).

These are just a few of the non-technical considerations that must be considered when deciding whether to increase the use of technology in the context of the healthcare industry. To properly develop a clearer picture of the specific socio-technical interactions involved in the introduction of automation technology into healthcare, a framework of analysis is needed. In previous research, the Actor-Network Theory (ANT) framework of analysis has been used, considering the interaction of human actors (physicians, patients, hospital administration, etc.) and the non-human actors of new technology (Cresswell et. al., 2010). In this case, the Interactive Sociotechnical Analysis (ISTA) and Unintended Consequences framework of analysis will be used (Harrison et. al., 2007). This combines aspects of ANT along with other frameworks to develop a model that focuses on five main interactions. In the context of healthcare information technology (HIT), those interactions can be seen in the diagram in Figure 2 between social systems, HIT-in-use, new HIT, and technical and physical infrastructures. These same interactions are applicable to the introduction of automation into the healthcare industry. In the first interaction, new automation technologies change the existing social and technical system. In the second, the existing infrastructure of healthcare facilities mediates the use of medical technologies. In the third, social systems (such as the current roles of physicians and patients) mediates healthcare technology uses. In the fourth, existing healthcare technology changes the social systems in place. Finally, in the fifth, these interactions between healthcare technologies and social systems lead to a redesign of new automation technology. These interdependent

interactions offer a framework to comprehensively analyze the effects and reactions between new automation technologies and the existing infrastructure and social systems.

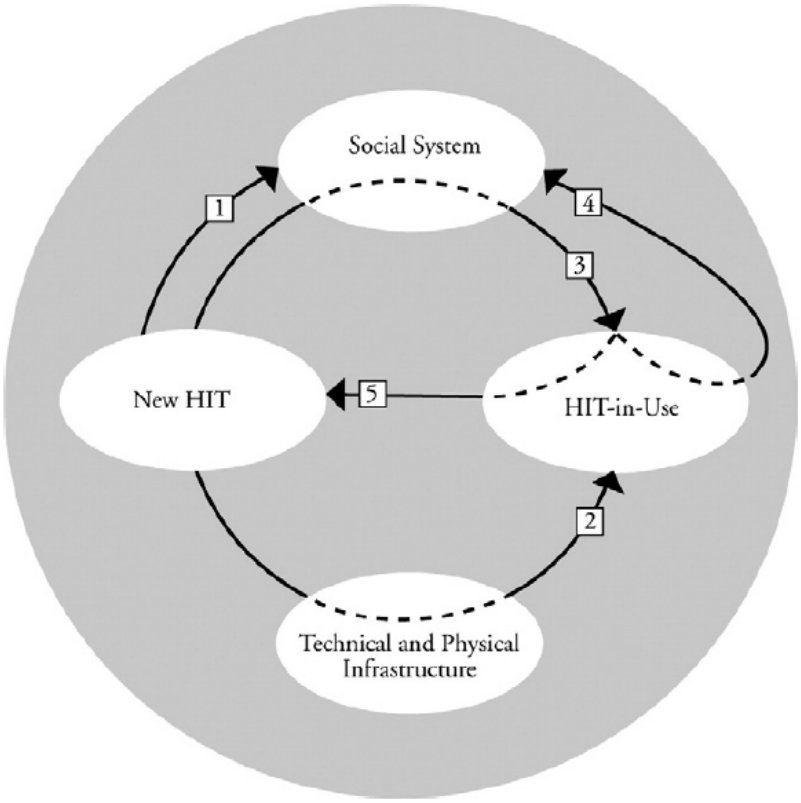

Figure 2: Diagram of Framework of Analysis. Source: Harrison et al (2007)

Research Question and Methods

The main question this thesis will seek to address is: how will the increased integration of automated technologies and processes into the healthcare industry affect existing standards of practice and roles of physicians? As with many industries, the continued implementation of new

technologies and automation into healthcare is seemingly inevitable (Angelov et. al., 2019), so it is important to investigate how these new technologies will change and interact with existing groups and systems.

Analysis of this overarching research question will be conducted with the use of primary research such as surveys and interviews with physicians as well a thorough review of prior literature and research articles that have sought to address similar questions. Interviews will contain questions related to the ways in which automation technology has been implemented in healthcare facilities and what the reaction has been from administrators and physicians. A sample list of questions can be found in Appendix A. Through responses from physicians to these questions, firsthand knowledge can be gained on how automated technology has been introduced and what its potential future implementation may look like based on the reactions of physicians and effect on existing healthcare systems. Beyond these interviews and surveys, research into prior literature and research articles will provide insights into the introduction of automation into healthcare and subsequent reaction on a broader scale. Through previously conducted surveys, case studies, and market tests of companies looking to implement their own technology into the healthcare industry, large amounts of data exist on the reactions from social groups and changes made to existing systems following the introduction of new technology into healthcare settings. From case studies done on new proposed automated management systems in small hospitals in Pittsburgh (Smith & Offodile, 2008) to companies looking to deploy a method of Robotic Process Automation at a large-scale in private healthcare centers (Bhatnagar & Jain, 2019), many contexts of previous research can offer a wide range of settings of analysis to establish a pool of results detailing what attempts have been made to deploy automation technologies in the healthcare industry and what the subsequent response has been.

Through both primary and secondary research, key commonalities can be drawn on some successes and failures of previously-implemented technologies as well as both hopes and concerns that physicians have for the potential future increase in automated technology in healthcare. This will help develop a model that can be analyzed with the ISTA framework, specifically exploring how these new technologies change the existing social system, while the existing social system and infrastructure mediates the implementation of automated technology.

Conclusion

With the use of mobile sensors and a predictive model, this capstone project will attempt to aid in the rehabilitation process of patients following ACL reconstructive surgery. By collecting metrics indicative of a successful recovery, rehabilitation physicians can conduct a more well-informed recovery process, which will in turn reduce the rates of reinjury in patients. However, the use of automated technology in this context must be carefully analyzed and mediated, as the rapid implementation of technology in healthcare raises issues in terms of its disruption to existing systems, privacy, security, and financial costs. Through the framework of ISTA and Unintended Consequences, interviews and secondary research will be conducted to explore the potential interactions of new automated technology and existing systems along with the benefits and consequences this presents.

References

Angelov, G. V., Nikolakov, D. P., Ruskova, I. N., Gieva, E. E., & Spasova, M. L. (2019). Healthcare sensing and monitoring. *Enhanced Living Environments* (pp. 226-262). Springer, Cham.

Benzidia, S., Ageron, B., Bentahar, O., & Husson, J. (2018). Investigating automation and AGV in healthcare logistics: a case study based approach. *International Journal of Logistics Research and Applications*, *22*(3), 273–293. https://doi.org/10.1080/13675567.2018.1518414

Bhatnagar, R., & Jain, R. (2019). Robotic process automation in healthcare-a review. *International Robotics & Automation Journal*, *5*(1), 12–14.

Coleman, R. D. (2019, December 5). Statistics on acl injuries in athletes. *SportsRec*. Retrieved September 27, 2021, from https://www.sportsrec.com/8077889/statistics-on-acl-injuries-in-athletes.

Cresswell, K. M., Worth, A., & Sheikh, A. (2010). Actor-Network Theory and its role in understanding the implementation of information technology developments in healthcare. *BMC medical informatics and decision making*, 10(1), 1-11.

Crowley, R., Daniel, H., Cooney, T. G., & Engel, L. S. (2020). Envisioning a Better U.S. Health Care System for All: Coverage and Cost of Care. *Annals of Internal Medicine*, 172(2_Supplement), S7.

Gurchiek, R. D., Choquette, R. H., Beynnon, B. D., Slauterbeck, J. R., Tourville, T. W., Toth, M. J., & McGinnis, R. S. (2019). Remote gait analysis using wearable sensors detects asymmetric gait patterns in patients recovering from ACL reconstruction. *2019 IEEE 16th International Conference on Wearable and Implantable Body Sensor Networks (BSN)*.

Harrison, M. I., Koppel, R., & Bar-Lev, S. (2007). Unintended Consequences of Information Technologies in Health Care—An Interactive Sociotechnical Analysis. *Journal of the American Medical Informatics Association : JAMIA*, 14(5), 542–549.

Ho, S. F., Thomson, A., Moylan, T., McGuckin, J., & Kerr, A. (2019). Automated movement feedback for recovering independence in the sit-to-stand movement in an older population: a pilot randomised controlled trial of a novel system. *OBM Geriatrics*, 3(4).

Kumar, R. Krishna. Technology and healthcare costs. *Annals of pediatric cardiology 4.1* (2011): 84.

Losciale, J. M., Zdeb, R. M., Ledbetter, L., Reiman, M. P., & Sell, T. C. (2019). The Association Between Passing Return-to-Sport Criteria and Second Anterior Cruciate Ligament Injury Risk: A Systematic Review With Meta-analysis. *Journal of Orthopaedic & Sports Physical Therapy*, 49(2), 43–54.

Lustgarten, S. D., Garrison, Y. L., Sinnard, M. T., & Flynn, A. W. (2020). Digital privacy in mental healthcare: Current issues and recommendations for technology use. *Current Opinion in Psychology*.

McGinnis, R. S., Redrado, J. B., Choquette, R. H., Beynnon, B. D., Slauterbeck, J. R., Tourville, T. W., & Toth, M. J. (2018, March). Wearable sensors capture differences in muscle activity and gait patterns during daily activity in patients recovering from ACL reconstruction. *2018 IEEE 15th International Conference on Wearable and Implantable Body Sensor Networks (BSN)* (pp. 38-41). IEEE.

Menzer, H., Slater, L. V., Diduch, D., Miller, M., Norte, G., Goetschius, J., & Hart, J. M. (2017). The Utility of Objective Strength and Functional Performance to Predict Subjective Outcomes After Anterior Cruciate Ligament Reconstruction. *Orthopaedic Journal of Sports Medicine*, 5(12), 232596711774475.

Meinert, E., Alturkistani, A., Brindley, D., Knight, P., Wells, G., & de Pennington, N. (2018). Weighing benefits and risks in aspects of security, privacy and adoption of technology in a value-based healthcare system. *BMC Medical Informatics and Decision Making*, 18(1).

Myer, G. D., Paterno, M. V., Ford, K. R., Quatman, C. E., & Hewett, T. E. (2006). Rehabilitation After Anterior Cruciate Ligament Reconstruction: Criteria-Based Progression Through

the Return-to-Sport Phase. *Journal of Orthopaedic & Sports Physical Therapy*, 36(6), 385–402.

Nyland, J. (2010). Update on rehabilitation following ACL reconstruction. *Open Access Journal of Sports Medicine*, 151.

Pratt, K. A., & Sigward, S. M. (2018). Detection of Knee Power Deficits Following Anterior Cruciate Ligament Reconstruction Using Wearable Sensors. *Journal of orthopaedic & sports physical therapy*, 48(11), 895-902.

Saxena, S., Sarkar, A., & Naik, A. K. (2020). SOCIO-ECONOMIC IMPACT OF SUPERVISED EXERCISE IN ACL REHABILITATION. *International Journal of Management (IJM)*, 11(4).

Smith, A. D., & Offodile, O. F. (2008). Data Collection Automation and Total Quality Management: Case Studies in the Health-Service Industry. *Health Marketing Quarterly*, *25*(3), 217–240.

Thimbleby, H. (2013). Technology and the future of healthcare. *Journal of Public Health Research*, 2(3), 28.

Tedesco, S., Crowe, C., Ryan, A., Sica, M., Scheurer, S., Clifford, A. M., ... & O'Flynn, B. (2020). Motion sensors-based machine learning approach for the identification of anterior cruciate ligament gait patterns in on-the-field activities in rugby players. *Sensors*, 20(11), 3029.

Webster, K. E., Feller, J. A., Leigh, W. B., & Richmond, A. K. (2014). Younger patients are at increased risk for Graft rupture and contralateral injury after anterior cruciate ligament reconstruction. *The American Journal of Sports Medicine*, 42(3), 641-647.

Appendix

Appendix A - List of Survey Questions for Physicians

Yes/No Question

- I have seen automated technology/automation implemented in my workplace.

Strongly Disagree/Disagree/Neutral/Agree/Strongly Agree Questions

- The amount of automated technology used in my healthcare facility has increased from when I began working.
- My healthcare facility should increase investments into automation and automated technology.
- My specific role as a healthcare worker has changed as a result of automated technology.
- The processes/standards of practice in my healthcare facility as a whole have changed as a result of automated technology.
- I think that the amount of automation used in the healthcare industry will increase in the future.
- Most current healthcare technology will become obsolete as a result of automated technology.
- I think that increasing the amount of automation in healthcare is a good thing.
- In general, my colleagues and administrative staff think that automation in healthcare is a good thing.
- In the future, there will be fewer careers in the healthcare industry as a result of automated technology.

Free Response Question

- Please use this space to write any additional thoughts you have about automated technology in the healthcare industry.