INCREASING INFLUENCE OF EXOSKELETON ON PHYSICAL THERAPY

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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

Imagine the possibilities offered by amplifying neuromuscular abilities with wearable robotics. The upper limb is a crucial part of numerous daily life activities, ranging anywhere from writing with a pencil to lifting a backpack, so upper limb functionalities affect the quality of life (Keramiotou et al., 2020).

Individuals typically assume that neuromuscular diseases are only relevant to the elderly. However, experts around the world counterargue that younger generations are at risk as well with statistics that put the severity of the issue into perspective. In the United Kingdom, the increase in the prevalence of neuromuscular disease patients was observed in all age groups with overall prevalence increase of 63% between 2000 and 2019 (Carey et al., 2021). In Ontario, Canada, between 2003 and 2014, the number of neuromuscular disease patients increased by 8% per year on average. Although the neuromuscular disease prevalence increased in all age groups, younger adults aged 18-39 years experienced the highest increase in neuromuscular disease prevalence of 11% per year (Rose et al., 2019). Additionally, a strong correlation exists between increasing upper limb neuromuscular disease prevalence in the younger generations and their exposure to electronic devices (Almomani et al., 2019). As electronic devices diversify and participate in larger portions of daily life activities, additional risk factors such as stress, sleep deprivation, and work environment contribute to even higher neuromuscular disease prevalence (Kazeminasab et al., 2022). In other words, neuromuscular diseases are beginning to influence a wider range of individuals regardless of age and residence.

Although no cure exists, numerous treatment methods exist. The current treatment methods for neuromuscular therapy can range anywhere from gene sequencing, therapeutic products, and occupational therapy. Depending on the type of neuromuscular disease, certain methods are more effective than others (Dowling et al., 2017). However, neuromuscular treatments may be unaffordable. Amyotrophic Lateral Sclerosis (ALS), Duchenne Muscular Dystrophy (DMD), and Myotonic Dystrophy (DM) are major types of neuromuscular diseases. A 2014 research paper calculated the average total annual cost per person as $63,693 for ALS, $50,952 for DMD, and $32,236 for DM (Larkindale et al., 2014).

One treatment method of increasing popularity is wearable robots, or exoskeletons. When a neuromuscular patient wears the exoskeleton, the exoskeleton will recognize and support the patient's intended actions. Exoskeletons are continuously diverging into multiple branches as researchers invent additional versions to meet specific needs (Lee et al., 2017).

While the exoskeleton industry is still at its early stages, the research will examine the effectiveness of exoskeletons as a neuromuscular disease treatment method. The continuous evolution of exoskeletons produces multiple technological and sociotechnical effects that influences the conventions of neuromuscular rehabilitation.

CASE CONTEXT

Explaining the current standards of the exoskeleton and rehabilitation industries is the goal of this section. Although exoskeleton may sound like a complicated technology, exoskeleton is simply a mechanical system consisting of sensors, actuators, feedback control, and mechanical design. The sensors measure user parameters. The control system processes and activates the actuation system. The actuation system moves the exoskeleton. The mechanical design refers to the characteristics of an exoskeleton that distinguish one exoskeleton from another exoskeleton (Vélez-Guerrero et al., 2021).

There are multiple sensor options. Although inertial measurement unit (IMU) and electromyogram (EMG) sensors that measure muscle signals are popular (Ganesan et al., 2015), crucial disadvantages, such as inconsistent signal quality and unknown muscle excitation magnitude, exist. For this reason, the electroencephalogram (EEG) sensors that directly extract brain signals indicating the magnitude of muscle excitement are widely utilized (Lee et al., 2022).

The interpretation of sensor signal is delivered to an actuator that moves the exoskeleton. When selecting an actuator, most exoskeleton models prioritize two factors: the masses of the exoskeleton parts and the actuator strength (Kavalieros et al., 2022). Based on experiments, pneumatic artificial muscles (PAM) can generate about 5-10 times greater force and 4-9 times greater energy-to-mass ratio than single-acting cylinders (Deaconescu & Deaconescu, 2022). For this reason, PAMs, which imitate flexion and extension of human muscles by varying the internal pressure, are frequently chosen as actuators.

The mechanical design aspect refers to unique characteristics that enhance user experience. Some characteristics that exoskeleton design engineers value are affordability, reproducibility, and portability. 3D-printed exoskeleton is a popular trend in the exoskeleton industry for offering multiple advantages. The lightweight parts of a 3D-printed exoskeleton allow the users and actuators to easily move the exoskeleton while minor adjustments are required for users of various sizes to possess an exoskeleton they can use at home (Esposito et al., 2022).

Ideally, exoskeleton is a powerful technology as well as an independent, affordable treatment method to neuromuscular disorder patients. However, the effects of exoskeleton on the current standards of neuromuscular rehabilitation must be considered as well. In other words, exoskeleton is a powerful technology that exerts influence beyond neuromuscular disorder patients.

If engineers are the providers of exoskeletons, physical therapists are the recipients of exoskeletons. The neuromuscular rehabilitation process is a set of arduous, lengthy steps for physical therapists. According to the American Physical Therapy Association (APTA), a person spends more than three years completing a Doctor of Physical Therapy program and passing the National Physical Therapy Examination after earning a bachelor's degree (APTA, 2022). A physical therapist typically spends 30-45 minutes per day, 4-5 times per week, and 8 weeks per patient (Louie et al., 2021). Another issue is physical therapist shortage where the aging population and increased public medical interest cause increased demand (Zhang et al., 2020). In contrast, physical therapist supply is declining due to the fear of COVID and poor working conditions.

As a result, exoskeletons are gaining popularity. Exoskeletons increase the independence of a patient by allowing the freedom of long duration exercise. Accordingly, the role of physical therapist may shift from guiding exercise activities to monitoring patient progress, which also minimizes the spread of COVID by preventing physical contact (González-Mendoza et al., 2022). As exoskeletons improve, the marginalized social group may change from neuromuscular patients experiencing disability to physical therapists losing necessity.

ACTOR NETWORK THEORY

The purpose of this section is to explain a theory that will be applied to analyze the research results. The particular interest is the change of relationships and roles between physical therapists and neuromuscular disorder patients as a result of the incorporation of exoskeleton into rehabilitation.

When a new technology is introduced, the acceptance of technology is a mandatory consideration. Since no technology is perfect, an unpromising technology is rejected by individuals. For example, research on utilizing exoskeletons to prevent injuries of construction workers revealed that some construction workers rejected exoskeletons due to reasons like lengthy training process and injuries due to exoskeleton failures (Choi et al., 2022). Another long-term challenge for the successful inclusion of exoskeletons is additional cost, such as time and research effort, necessary to persuade the individuals by ensuring the credibility of exoskeletons.

To further analyze the sociotechnical aspects of exoskeletons, Bruno Latour's arguments are noteworthy. Latour offers Actor-Network Theory as a way to analyze the world as an enormous network of intertwined influential relationships amongst numerous actors of the network. In other words, Latour's argument serves as the midpoint between technological determinism and social construction of technology where even the most negligible actor is able to affect other actors. Parts of Latour's arguments especially valuable when considering the sociotechnical effects of exoskeleton are *delegation* and *program of action*. Delegation, in general, means transfer of work. Delegation to nonhuman is when an artifact takes over the manual work of humans. To better explain delegation, Latour identifies a groom that closes a door instead of humans as an example. On the other hand, program of action states that instructions are inscribed to reflect human values and encourage certain behaviors. As an example, Latour mentions that if a car is moving, then the driver has a seat belt. Through this example, Latour argues that there are a set of sociological and logical rules to promote safety. A network full of human and nonhuman actants such as policymakers, police officers, cars, and road signs collaborate to enforce the seatbelt rule (Latour, 1992).

An article by the University of Twente provides additional examples to explain the components of Latour's Actor-Network Theory. The article uses the gun as an example and provides a theoretical scenario to explain program of action. If a protagonist wants to take revenge on an antagonist but does not have enough power, the protagonist may utilize a gun. In this case, the program of action of the gun, or the ability to shoot, is borrowed to satisfy the program of action of the protagonist, which is the willingness to revenge on the antagonist. The article brings up speed bump as an example of delegation. The article describes speed bump as "a lump of concrete with an inscribed program of action" to symbolize its role to slow drivers without the need of a traffic sign or a police officer (University of Twente, 2023).

The introduction of exoskeleton adds another actor to the network that impacts the preexisting direct relationship between physical therapists and neuromuscular disorder patients. The use of exoskeletons in neuromuscular rehabilitation aligns with Latour's ANT framework because the manual procedures conducted by physical therapists may be assigned to exoskeletons. For this reason, arguments by Latour are suitable as the foundation of the research strategy.

RESEARCH QUESTION AND METHODS

To what extent will exoskeletons influence physical therapy? This question is valuable for predicting potential impacts of exoskeletons on the physical therapy industry while the exoskeleton industry is at its infancy. Through the lens of Actor-Network Theory, I predict that exoskeletons will increase influence on physical therapy and eventually become an essential physical therapy equipment as time passes.

I planned out two research methods to answer the research question. One research method was applying thematic analysis method to a scientific journal. The source titled, “Exoskeletons: State-of-the-Art, Design Challenges, and Future Directions,” discussed current challenges, future of exoskeletons, and ethical considerations (Agarwal & Deshpande, 2019). Thematic analysis is identifying patterns in a set of qualitative data (Kiger & Varpio, 2020). This research strategy identified prerequisites for the future incorporation of exoskeletons into physical therapy from the perspective of an engineer.

For the sake of diversity and bias, a second research method was applying thematic analysis after surveying and interviewing physical therapists. I reached out to physical therapists and Kinesiology students and professors in Charlottesville. The survey provided a photograph of an upper limb exoskeleton, explained the necessary background information about exoskeleton, and asked questions to gather data from physical therapists. The survey asked five rating scale questions where the respondents had to provide an answer on a scale from zero to ten. The interview was based on five free response questions where the respondents responded in several sentences. With the rating scale and interview questions, I acquired a set of quantitative and qualitative data. In contrast to the first research strategy, the second trategy suggested a few main ideas regarding the potential impacts of exoskeletons on the future of rehabilitation from the physical therapist standpoint. Since the interviews from physical therapists and the first research method both yielded qualitative data, the two types of qualitative data were compared to observe any discrepancies between the viewpoints of physical therapists to the viewpoints of engineers.

RESULTS

The findings were summarized into two major takeaways. First, several drawbacks of current exoskeletons must be addressed before exoskeletons are widely incorporated into rehabilitation. Second, future exoskeletons will increase their influences on physical therapy. The first takeaway was deduced by comparing engineer perspective to physical therapist perspective. The second takeaway was extracted by analyzing the survey responses from 25 physical therapists,

Comparison of Physical Therapist and Engineer Perspectives on Exoskeleton

Research suggested that exoskeleton is an imperfect technology. Predicting the impacts of an ineffective technology is meaningless since the technology is discarded by users from the beginning. For this reason, examining the ways exoskeletons may shape the future of rehabilitation must begin by evaluating the usefulness of exoskeletons. The approach was identifying a few disadvantages that may prevent the incorporation of exoskeleton into rehabilitation.

The first evidence comes from the interview where each interviewee submitted a brief explanation on reasons not to use exoskeletons during rehabilitation. Some interviewees elaborated on one factor, while others stated multiple factors. The responses were categorized into six themes.

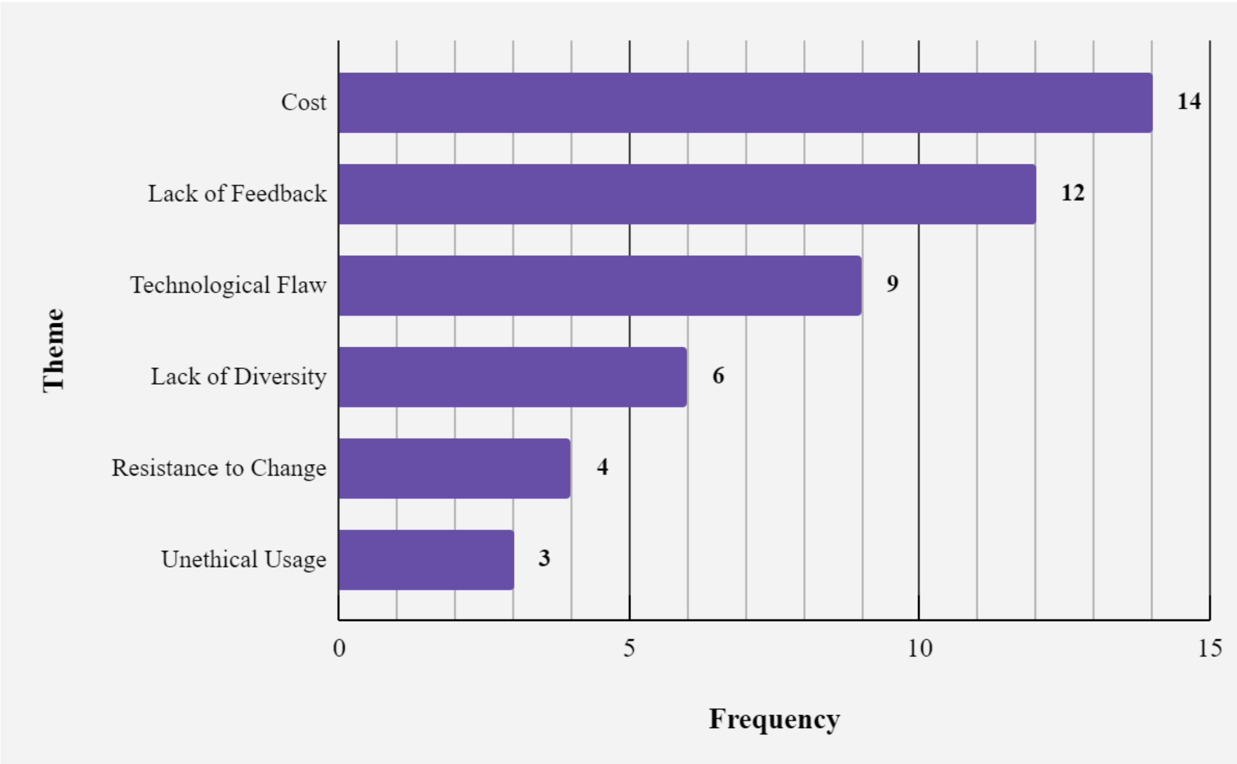

Figure 1. Disadvantages of exoskeletons identified by interviewee. (Created by Lee, 2023)

Since interviewees were physical therapists, their responses prioritized factors related to patient experience. For example, most respondents feared that exoskeletons may not be affordable for patients. Some believed exoskeletons were ineffective due to the inability to communicate with patients, and others predicted that mechanical failures of exoskeletons will cause injuries. This evidence is valuable for two reasons. First, the responses were from physical therapists that understand the rehabilitation process and will become stakeholders if exoskeletons are incorporated into physical therapy. Second, the aforementioned disadvantages of exoskeletons are crucial considerations as engineers expand the exoskeleton industry.

The second evidence resulted from applying the same approach on a scientific journal titled, “Exoskeletons: State-of-the-Art, Design Challenges, and Future Directions” by Agarwal and Deshpande. The source content was categorized into the same six categories.

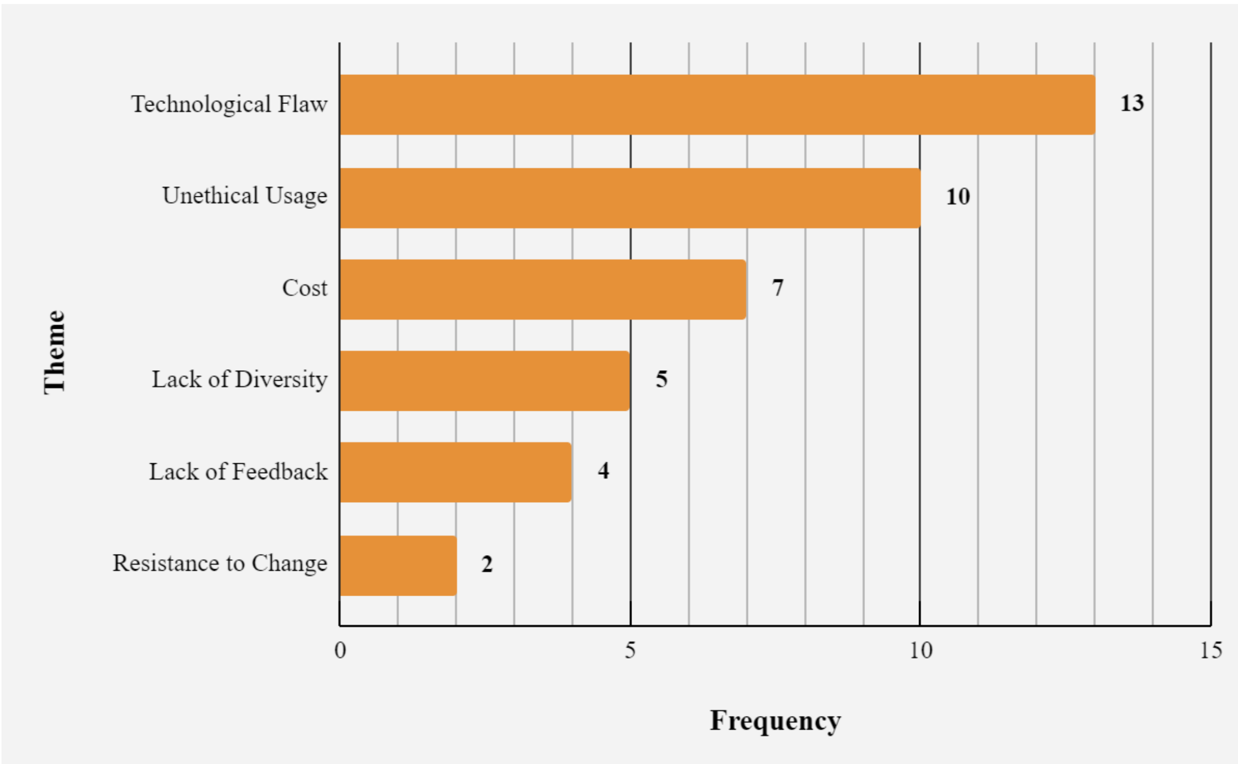

Figure 2. Disadvantages of exoskeletons identified by a scientific journal titled, “Exoskeletons: State-of-the-Art, Design Challenges, and Future Directions”. (Created by Lee, 2023)

The authors of the scientific journal are robotics researchers at the University of Texas at Austin, which implies that the journal analyzed disadvantages of exoskeletons from the perspectives of engineers (The University of Texas at Austin, 2023). For this reason, the journal focused on common engineering values such as functionality, ethics, and cost.

When comparing the scientific journal to the interview responses, patterns are observed. First, the disadvantages of exoskeletons identified by users, or physical therapists, and designers, or engineers, are separable into six mutual categories. Second, although the category ranking varied depending on the perspective, technological flaw and cost were highly concerned by both physical therapists and engineers. The six major disadvantages represent possible reasons why exoskeletons may not be utilized in rehabilitation, but further growth of the infant exoskeleton industry will produce more promising exoskeletons (Gorgey, 2018).

Interpretation of Survey Responses

The more exoskeletons improve technologically, the more exoskeletons contribute to rehabilitation. This takeaway is intended to analyze how the physical therapy will adjust to the increasing popularity of exoskeletons in the future. Table 1 outlines the survey questions and offers valuable results.

Question Number	Question Statement	Average Response
1	Exoskeleton is an effective rehabilitative therapy. (*0 = Strongly Disagree & 10 = Strongly Agree*)	**6.80**
2	Future rehabilitative procedures will incorporate exoskeletons. (*0 = Strongly Disagree & 10 = Strongly Agree*)	**6.76**
3	To what extent will future rehabilitative procedures rely on exoskeletons? (*0 = Independent & 10 = Influential*)	**5.20**
4	Physical Therapist vs. Exoskeleton: Which is a more effective rehabilitative therapy? (*0 = Physical Therapist & 10 = Exoskeleton*)	**2.16**
5	Exoskeletons will "eventually" replace physical therapists. (*0 = Strongly Disagree & 10 = Strongly Agree*)	**0.68**

Table 1. Overview of the survey questions and responses. (Created by Lee, 2023)

According to Question 1, exoskeleton usage in rehabilitation was considered effective. The definition of effectiveness to medical professionals is the extent to which intended results are achieved by an action (Burches & Burches, 2020). In other words, the majority of respondents believed that patient rehabilitation would be successful even with exoskeleton involvement.

Responses to Question 2 implied that future rehabilitation will most likely incorporate exoskeleton. Physical therapists will incorporate exoskeletons into future rehabilitation because exoskeletons offer advantages to patients as well as physical therapists. Exoskeleton will reduce burden and clinical cost for physical therapists (Ekso Bionics, 2023).

Based on Question 4, physical therapists believed physical therapy is more effective than exoskeleton. Such a trend can be explained by reiterating the findings from Figure 1. One of the biggest factors contributing to the mistrust of functional capabilities of exoskeletons was lack of feedback, especially because patients heavily value communication (Marinov, 2016).

Responses to Question 5 suggested similar trends as responses to Question 4 because both argue that exoskeletons cannot replace physical therapists. Question 5 provided an insightful answer to the research question. Given that sixteen out of twenty-five respondents were certain that exoskeleton can never replace physical therapists by submitting a zero to the question, the introduction of exoskeletons will create a triangular relationship amongst physical therapist, patient, and exoskeleton. (Bortole et al., 2015).

The possibility of the triangular relationship was supported by Question 3 average response, which stated that the relationship between physical therapy and exoskeleton will be neither independent nor influential in the future. Interestingly, responses to Questions 1 and 4 served as supporting evidence. Although Question 4 suggested that physical therapists found physical therapy more effective than exoskeleton, Question 1 indicated that physical therapists still considered exoskeletons effective.

Physical therapists believed that introduction of exoskeleton in physical therapy will mean more than a simple change in the relationship between physical therapist and neuromuscular patient. Additional outcomes that physical therapists were concerned about are summarized in Figure 3 below.

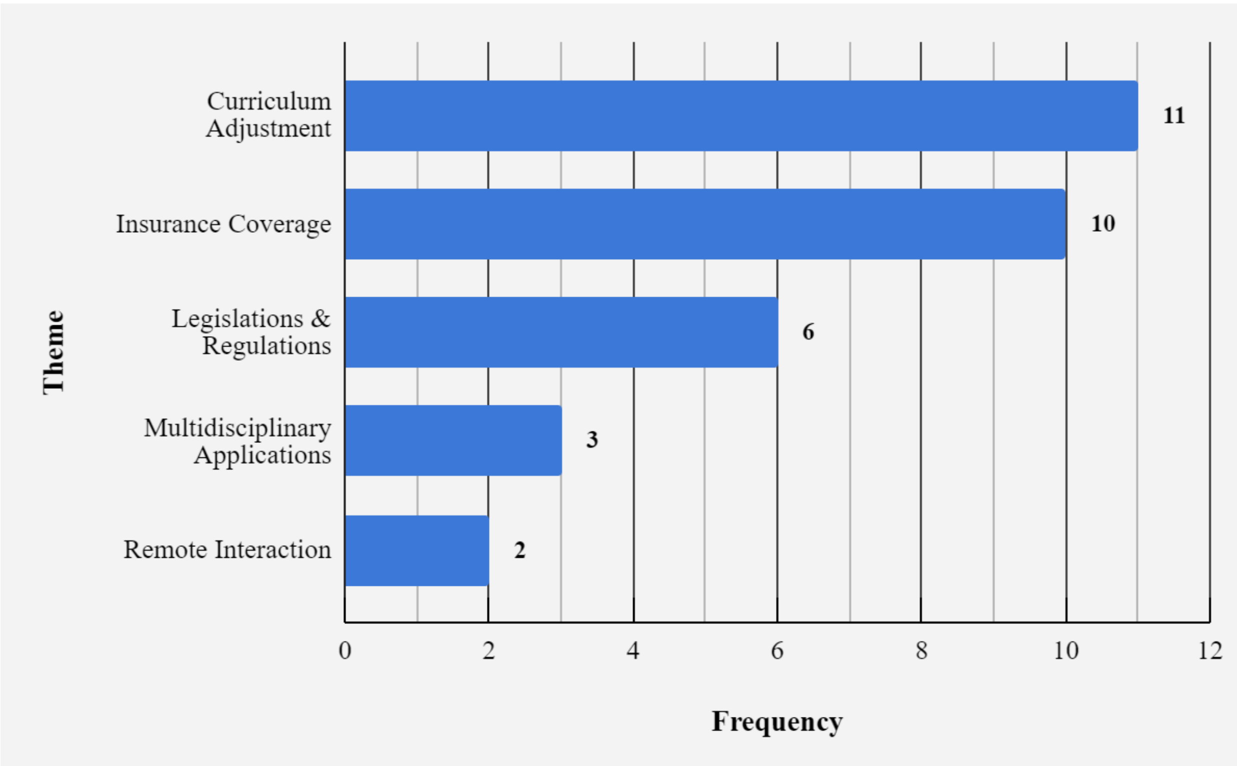

Figure 3. Overview of the interview responses on potential implications of incorporation of exoskeleton into rehabilitation. (Created by Lee, 2023)

Figure 3 suggests that increased usage of exoskeletons will influence the curriculum so that physical therapists are responsible for managing and monitoring multiple types of exoskeletons. Additionally, respondents expected changes in the healthcare infrastructure such as insurance and legislation and acknowledged that exoskeletons may alter the nature of physical therapy and possibly utilized in other fields such as military and construction.

DISCUSSION

Exoskeleton will exist at the midpoint between physical therapist and neuromuscular patient to assist both sides. The research suggested that physical therapists are willing to incorporate exoskeletons into physical therapy, assuming technological improvements of exoskeletons over time. As a result, a triangular relationship amongst physical therapist, neuromuscular patient, and exoskeleton will form, which aligns with Latour's Actor-Network Theory. According to *program of action*, exoskeleton will guide the patient through the rehabilitation steps, which helps the patient by allowing some degree of independence. Knowing this, physical therapist will assign the previously manual task of "rehabilitation guidance" to the exoskeleton, satisfying the *delegation* aspect of the Actor-Network Theory. Then, physical therapist focuses more on monitoring patient progress and maximizing patient experience, and the patient rewards the physical therapists for the service.

Additionally, Figure 3 identifies changes in the curriculum and insurance coverage as the two most significant outcomes potentially caused by the introduction of exoskeleton. Curriculum change is a crucial requirement for physical therapists to adapt to the evolving conventions of physical therapy, so they maintain their necessity and ability to provide service. Insurance coverage is another interest of physical therapists because if patients are unable to afford the emerging exoskeleton equipment, physical therapists are unable to provide service to patients. In summary, Latour's Actor-Network Theory is applicable to the research topic because simply adding a factor called exoskeleton will modify numerous other factors.

Engineering products are increasing contributions to medical procedures. Nanorobot, which is a miniature robot about 10 times smaller than a blood cell, is another example following the trend. Nanorobot has challenges such as cost, material, and regulation and advantages like the ability to complete complicated operations and reduced human error. Nanorobot will produce three effects. First, nanorobot was originally intended for diagnosis, but its proven effectiveness expanded the range of purposes and applications to surgery, treatment, and monitor and cancer, dentistry, and diabetes, respectively. Second, current conventions of therapy procedure, medical education, healthcare, and regulations will adjust to take nanorobot into account. Third, the responsibilities of a surgeon will focus more on monitoring patient progress instead of conducting medical procedures (DelveInsight, 2022).

The most significant limitation of this research is bias caused by lack of diversity. One type of bias is geographical bias. All survey respondents are from Charlottesville, VA. Some survey respondents even belong to the same physical therapy center where they operate on the same set of patients, tools, and procedures. One effect of geographical bias on my data is reduced validity, meaning the observed trends are possibly skewed by a group of individuals sharing similar experiences (Skopec, 2020). Additionally, the takeaways cannot be generalized to the entire United States because different regions have respective conventions of rehabilitation. Another bias type is age bias. The age distribution of survey respondents is unbalanced, where age groups 40 - 49 and 60 - 69 have one respondent each, while age group 20-29 has thirteen respondents. This uneven distribution could have skewed the data, especially because respondents in the age group 20 – 29 are mostly students with limited physical therapy experience (Cutler 2005).

Future research will focus more on quality than quantity. Current research is conducted by spreading the online survey link through limited connections, so the results are influenced by geographical and age bias. Future research will likely utilize social media like LinkedIn to schedule interviews. Doing so offers two advantages. The first advantage is my ability to consider diversity before scheduling interviews, so geographical and age bias will be minimized. The second advantage is that I directly participate in the data collection process, and the data will be much more legitimate than survey responses submitted remotely.

The findings of this research provide valuable guidance to engineers by clearly defining limitations and motivations of exoskeletons. Engineering design process is complicated due to the number of variables involved, so priorities determine the final design. The research lists factors such as cost, technological reliability, and ethics that engineers must consider for future developments. On the other hand, physical therapists emphasize that technological advancement and diversification of exoskeletons will leave a significant footstep in rehabilitation. Successful incorporation of exoskeletons into rehabilitation will be an iterative process full of communications between engineers and physical therapists.

CONCLUSION

Exoskeleton is a wearable robot designed to assist neuromuscular disorder patients with rehabilitation. Although exoskeleton opens up a new world for the patients, its impacts are beyond patients. Successful incorporation of exoskeleton into rehabilitation is a gradual process, and the challenges are affordability, technical design improvement, and ethical consideration. Once the challenges are overcome, exoskeleton will gradually increase influence on physical therapy and eventually create a triangular mutualistic relationship with physical therapist and neuromuscular patient. The research is valuable for analyzing the long-term technical and sociotechnical effects of exoskeleton while the exoskeleton industry is at its infancy.

Exoskeleton is only one example of the general trend where engineering is redefining the conventions of medical procedures.

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