Scaling up high-dose, high-intensity neurorehabilitation: A case study on cost-effective implementation

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Executive Summary

Stroke is the third-leading cause of death and disability worldwide, and its incidence and prevalence are projected to continue to increase. Yet, the current standard of care for stroke rehabilitation has struggled to demonstrate significant improvement in upper limb mobility, leading to persistent motor deficits in the majority of stroke patients. Three key components contribute to this problem: low dosage of rehabilitation, the constraint of a 1:1 therapist-to-patient ratio, and the high costs associated with in-person therapy.

This case study examines the potential for high-dose, high-intensity rehabilitation therapies to address the growing burden of stroke. We examined 7 different rehabilitation therapies based on their prescribed therapy hours, therapist-to-patient ratio, proportion of therapy done remotely, and clinical outcomes measured by the Fugl-Meyer Upper Extremity (FM-UE) assessment. The FM-UE scores were used as the primary outcome measure. The analysis also considered the cost estimates for each therapy, including labor costs, equipment costs, and travel costs.

The case study employed linear regression analysis to assess the importance of these 3 components to FM-UE outcomes. The probability of therapy success for individual patients was then evaluated by simulating hypothetical patients based on the reported FM-UE scores and assessing the proportion of patients achieving a clinically significant improvement.

The results of the analysis indicated that high-dose, high-intensity neurorehabilitation therapies have the potential to deliver meaningful clinical outcomes for stroke patients. Although in-person therapies have a larger probability of treatment success compared to patients attending a remote rehab therapy at an individual level, remote therapy shows a greater potential of success for more patients as population demands increase.

In conclusion, high-dose, high-intensity neurorehabilitation offers a promising approach to address the growing burden of neurological disorders, specifically in stroke rehabilitation. By implementing a remote, technology-assisted approach, we can improve rehabilitation outcomes across the population in a cost-effective manner with greater scalability.

Introduction

Neurological disorders pose a significant burden on healthcare systems worldwide as they represent the leading cause of disability and the second-leading cause of death worldwide. Unfortunately, given an aging population in many parts of the world, this burden is projected to rise. Thus, healthcare providers, policymakers, payers, and other stakeholders must ask: how can we tackle the growing burden of neurological disorders in a cost-effective manner?

In this case study, we explore the potential for high-dose, high-intensity outpatient rehabilitation therapies to address this question. We focus on outpatient rehabilitation for patients who have experienced a stroke–a blockage of blood supply to the brain or a burst blood vessel in the brain that more commonly occurs in older individuals. We focus on stroke because it is the third-leading cause of death and disability combined (Feigin et al. 2021), and the burden is expected to grow given an aging population and that global stroke incidence and prevalence has increased by 70% and 85% from 1990 to 2019, respectively (Feigin et al. 2022).

Among the many components of stroke management, outpatient stroke rehabilitation is the most obvious tool to leverage because it has the longest therapeutic window and can directly improve a patient's quality of life. For example, more than 80% of stroke patients will experience persistent motor deficits that make it difficult to use the upper limb (Rathore et al. 2002). Unfortunately, the current standard of care for stroke rehabilitation has struggled to demonstrate true recovery in upper limb mobility post-stroke. Under current approaches to care, the majority of these patients will live with physical impairments that limit the quality of their daily lives and decrease their well-being (Wyller et al. 1997; Stewart and Cramer 2013). This further complicates the motivating problem: **How can we tackle the growing burden of neurological disorders *while improving rehabilitation outcomes* in a cost-effective manner?**

Components of the Problem

Dosage of rehabilitation is too low

The majority of post-stroke patients engage in physical and occupational therapies wherein they engage in repetitions of movement practice to improve their ability to move their body and perform activities of daily living. According to much of the scientific literature, large doses of practice – hundreds of daily movement repetitions – may be required to produce lasting and meaningful change for those in outpatient stroke rehabilitation (Lang et al. 2009; Lohse, Lang, and Boyd 2014; Lang, Lohse, and Birkenmeier 2015; Jeffers et al. 2018). These recommendations also appear in best practice rehabilitation guidelines put forth by stroke organizations (e.g., Teasell et al. 2020). However, in practice, the dosage of therapy provided to post-stroke patients is often substantially lower (Lang et al. 2009; Clarke et al. 2018; Sheehy et al. 2019), and so many patients do not achieve meaningful movement recovery. Therefore, increasing rehabilitation dosage will be a key factor to address the motivating problem.

Constraints of a 1:1 therapist-to-patient ratio

Standard clinical rehabilitations guidelines often suggest a 1:1 therapist-to-patient ratio (e.g., Hebert et al., 2015). If the expectation is that outpatient rehabilitation continues to offer a 1:1 ratio, payers should anticipate a rapid rise in the cost to provide rehabilitation. However, even if it would be possible to cover these increasing costs, there is a concern that there will be insufficient physical and occupational therapists available to guide rehabilitation. For example, both the United States (Lin, Zhang, and Dixon 2015) and Canada (Statistics Canada 2023b, 2023a) are anticipating a staffing shortage of both occupational and physical therapists into 2030. Given the staffing concerns and cost considerations, it is likely that a solution to the motivating problem will be a therapy approach that offers sufficient patient success with a lower therapist-to-patient ratio. This can take the form of having less one-on-one supervised time with a rehabilitation therapist, or having rehabilitation therapists monitor more than one patient simultaneously.

Monetary costs of in-person therapy can be prohibitively expensive

Costs associated rehabilitation therapies are extensive and include monetary costs associated with labour, equipment, and travel. Labour costs to pay the salaries of highly trained therapists alone can be substantial for high-dose rehab therapies. In addition, the majority of outpatient stroke rehabilitation occurs in-person at clinics, and it is generally expected that patients travel to and from the clinic to obtain treatment. Therefore, travel costs can directly impact who can access outpatient rehabilitation. Unfortunately, there is great inequity in patients' distance to stroke clinics. Patients in rural and remote regions must travel much further, often at their own expense, to access rehabilitation services compared to patients in urban regions (Doherty et al. 2021). This access inequity is likely part of the reason why stroke patients in rural and remotes regions spend less time and demonstrate lower adherence in rehabilitation (Hall et al. 2018), and have poorer overall outcomes (Thompson et al. 2022). Therefore, equitable and effective rehab therapies must be cost-effective those that minimize costs while still delivering meaningful clinical improvements to patients.

Defining a good solution

Given the three components to the problem, a good solution to tackle the growing burden of neurological disorders while improving rehab outcomes in a cost-effective manner will be one that:

1. increases rehab therapy dosage;
2. can deliver rehab therapy with < 1:1 therapist-to-patient ratio;
3. is low cost compared to alternative rehab therapies.

An ideal solution will be able to address these three components even as the number of patients increases, all else being equal.

Methods

Overview

The suitability of 7 rehab therapies were examined using data obtained from their respective published papers (Ward, Brander, and Kelly 2019; Cramer et al. 2019; Daly et al. 2019; McCabe et al. 2015; Cramer et al. 2020; Dodakian et al. 2017). Specifically, the following information from each therapy were obtained: prescribed therapy hours; prescribed number of therapy sessions; the therapist-to-patient ratio; the proportion of therapy time done remotely; the number of patients who were assessed at baseline and follow-up; and the mean and standard deviation within-participant change in the Fugl-Meyer Upper Extremity scores (see below). A subset of this information is plotted in Figure 1.

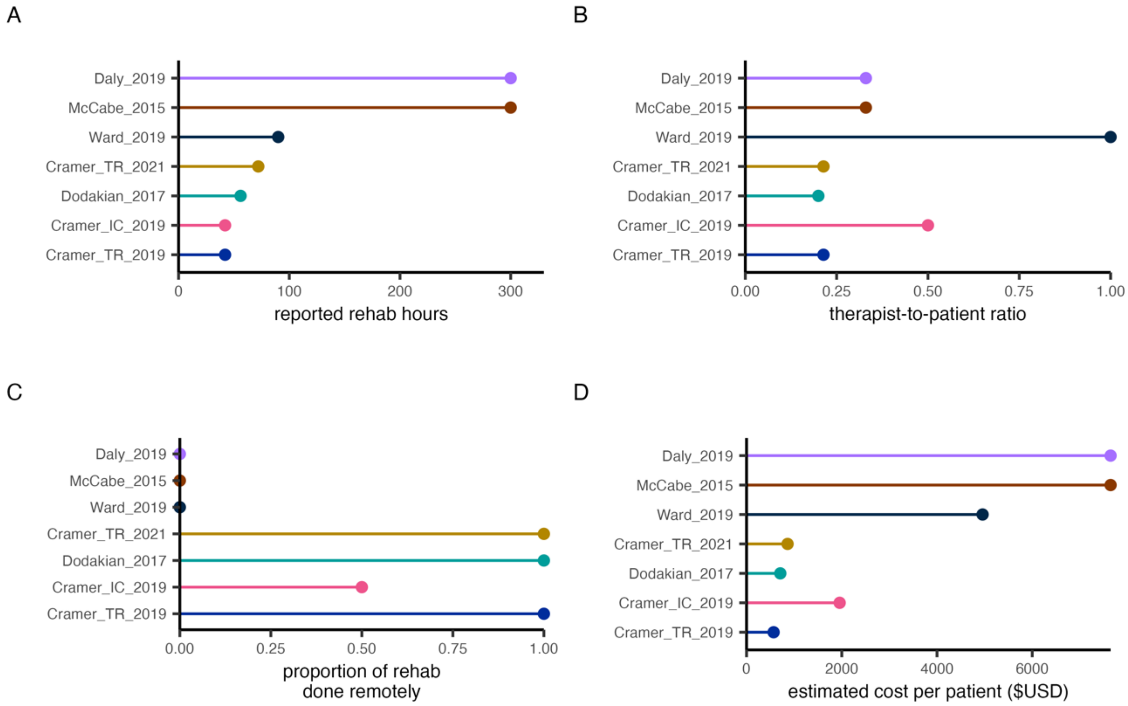

Figure 1. Comparison of the 7 different therapies on the total prescribed therapy hours (**A**); the estimated therapist-to-patient ratio (**B**); the proportion of treatment each patient received remotely (**C**); and the estimated cost per patient (**D**, see methods).

These 7 therapies are generally all high-dose and high-intensity, but differ in where the rehab therapy is offered (in clinic vs. remote) and the therapist-to-patient ratio (please refer to the labour cost section of appendix A for a technical note about the therapist-to-patient ratios). Generally, the therapies followed 1 of 3 formats.

The first rehab therapy format (therapies *Ward_2019*, *McCabe 2015*, and *Daly_2019*) uses high-dose, high-intensity rehab in an in-person setting. These therapies rely on a large team of therapists to deliver tens-of-hours of supervised (1:1 therapist-to-patient ratio), in-clinic treatment focusing on rehabilitation of the upper limb. Therapies that offer high-dose, high-intensity rehabilitation are gaining greater attention in the outpatient setting. Further details of each therapy of this type can be found in the respective papers (McCabe et al. 2015; Daly et al. 2019; Ward, Brander, and Kelly 2019).

The second rehab therapy format (therapy *Cramer_IC_2019*) employs a similar high-dosage approach, but allows patients to perform half of the rehab therapy unsupervised at home (Cramer et al. 2019). This results in a lower the therapist-to-patient ratio (as half the time is spent unsupervised), but also reduces the monetary travel costs associated with travel to obtain treatment.

The third rehab therapy format (therapy *Cramer_TR_2019, Dodakian_2017*, *Cramer_TR_2021*) is also high-dosage but is administered entirely remote using internet connected software and hardware (Dodakian et al. 2017; Cramer et al. 2019, 2020). Specifically, a range of technology instruments – like motion tracking controllers and interactive grip devices – are delivered to a patient's residence, and patients use these various hardware devices to perform gamified versions of rehab therapies. Given the remote nature of this rehab therapy structure, monetary costs associated with travel for treatment are no longer of great concern. Furthermore, these therapies generally have very low therapist-to-patient ratios given the more automated format of treatment. Patient adherence is slightly lower in remote telerehab, formats, however, clinical outcomes in patients who complete this therapy structure remain high (y-axis in figure 1).

Using the Fugl-Meyer Upper Extremity Assessment as a primary outcome measure

Stroke patient recovery in upper limb (arm/wrist/hand) motor impairment is commonly assessed by the Fugl-Meyer Upper Extremity (FM-UE) assessment (Fugl-Meyer et al. 1975). Given the ubiquity of this measure in stroke rehabilitation literature, the change in FM-UE scores were the primary means by which different therapies examined in this case study were evaluated for clinical success. It is a widely used, reliable, and validated measure of motor impairment in patients with stroke (Gladstone, Danells, and Black 2002) that provides a global assessment of upper limb movements in and out of synergy patterns (i.e., the ability to produce individuated movements about one joint without involuntary movement about a related joint, like moving about the shoulder without bending at the elbow). It consists of 33 items, where each item is scored on a 3-point ordinal scale (0=unable to perform, 2=able to perform), yielding a total possible score of 66. Higher scores indicate less impairment. Stroke patients that increase their FM-UE from pre- to post-rehabilitation assessments are considered to have experienced a degree of improvement. The minimal clinically important difference (MCID) for the FM-UE ranges between 4.25 and 7.25 points (Page, Fulk, and Boyne 2012).

It is important to note that the FM-UE was not designed to measure overall impairment after stroke, but rather a single component of impairment (Krakauer et al. 2021). We therefore attempted to include additional outcome measures in this analysis – like the Action Research Arm Test – but were ultimately limited to use only the FM-UE clinical assessment because it was the sole measure included in all the compared studies.

Cost estimates for each rehab therapy

Cost estimates for an individual patient to receive each therapy as explained in the associated papers are plotted in Fig. 1D. For each therapy, the costs of three components (labour costs, equipment costs, and travel costs) were estimated and then summed to obtain a single cost estimate for each therapy. Costing details are provided in appendix A.

Linear regression between rehabilitation therapy components and FM-UE outcomes

As a first analysis, we examined which of 3 features of each therapy meaningfully contributed to clinical improvements. To do this, we performed OLS, using the total scheduled therapy hours, therapist-to-patient ratio, and the proportion of treatment hours offered remotely to predict the mean changes in FM-UE across the 7 evaluated therapies. This model was used as a baseline model against which we compared the fits of new OLS models fit after shuffling only the values in one of the three predictive features. The increase in the model error after shuffling data for only one of the 3 features reveals the importance of the shuffled feature: an increase in error relative to the baseline (unshuffled) model suggests that the feature for which data was shuffled offers some degree of unique predictive ability. This shuffling and model fitting procedure was done 1000 times per feature, with the resultant model errors plotted in Fig. 2D.

Probability of rehabilitation therapy success for an individual patient

To evaluate the probability that a specific rehabilitation therapy could yield clinical improvement in an individual participant, hypothetical patients were simulated using the data obtained for each of the 7 therapies. Specifically, given the mean μ and standard deviation σ of the within-participant change in the FM-UE scores for a specific therapy, we simulated a batch of scores $\boldsymbol{x}$ reflecting each hypothetical patient's change in FM-UE from baseline (pre-rehabilitation) to follow-up (some time point after rehabilitation) according to a normal distribution $\boldsymbol{x} \sim N(\mu, \sigma)$. The number of hypothetical patients per simulation matched the number of patients reported in each respective therapy. Means and standard deviations of the simulated patient batches were confirmed to approximate the true values from each paper (see Fig. S1 in appendix B). In instances where the median and range – but not mean and standard deviation – of FM-UE scores were reported (Dodakian et al. 2017; Ward, Brander, and Kelly 2019; Cramer et al. 2020), we estimated the mean and standard deviations as per Hozo, Djulbegovic, and Hozo (2005). Each simulated batch of patients (i.e., set of simulated change in FM-UE scores) was then assessed for therapy success. Specifically, we counted the proportion of scores that were equal to (or greater than) a specific MCID threshold of the FM-UE. This yielded probability estimates for clinical improvement of varying degrees (for FM-UE score increases between 4.25 and 7.25 – the MCID range). The simulation process was repeated 100 times for each rehab therapy, and the results were then averaged across simulations for analysis and plots.

Estimating rehab success when scaling-up coverage

Each therapy was evaluated on its ability to yield clinically important outcomes for a group of patients of increasing size. Specifically, we considered a hypothetical scenario wherein there was a maximum budget of $1 million USD available to cover the costs (labour, equipment, and travel costs) for a set of stroke patients requiring outpatient rehabilitation. Given the previously estimated probabilities therapy success rates, we were able to compute how many patients (of those that could be treated given the budget) could be "successfully" treated (given a specific MCID criteria for the FM-UE). Therapies that could sustain their patient success rates were considered good candidates for high-dose, high-intensity rehabilitation therapies that could be scaled up to meet future demands.

Code availability

The data and code used to perform the analyses and produce figures for this case study report are available on github (Arbuckle 2023).

Results

Importance of rehab components on mean FM-UE scores

Unsurprisingly, the mean FM-UE change was positive in each of the 7 therapies, demonstrating all therapies provided some reduction in motor impairment. The key question, however, is whether one specific feature was most impactful. Therefore, we first examine how 3 features of each of the 7 examined therapies (total rehab hours; therapist-to-patient ratio; and proportion of the rehab that was offered remotely) relate to the mean FM-UE score changes from pre-rehabilitation to follow-up assessment (Fig. 2). To do this, we calculated the fit of thousands of linear model to the FM-UE scores, where each model had the data for one feature shuffled, effectively breaking any association between that feature and the clinical improvement (see methods). All three therapy features accounted for some unique contribution to the observed clinical outcomes, with the most important feature being the therapist-to-patient ratio: the more direct oversight a patient received from a therapist, the greater their improvement.

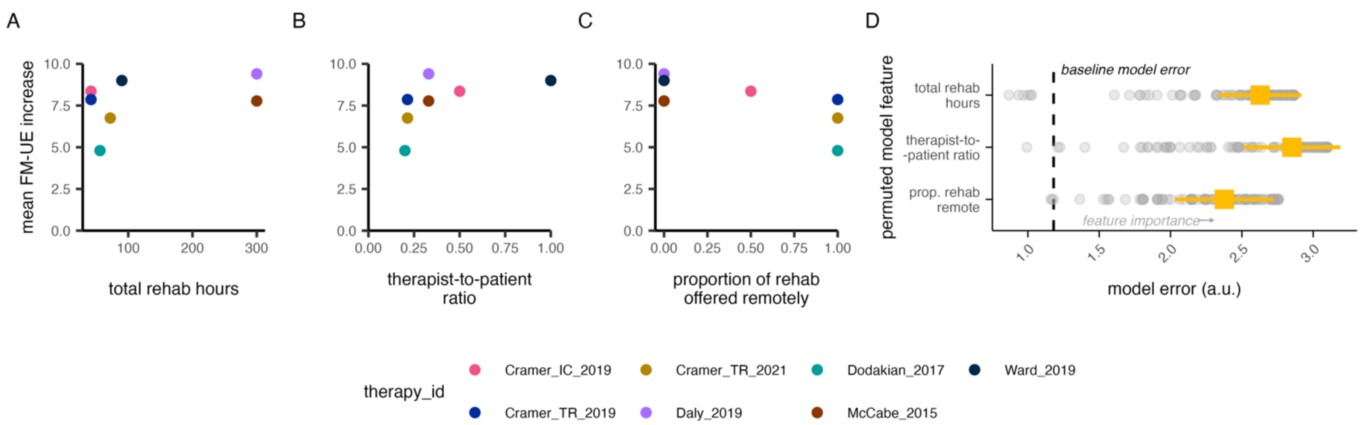

Figure 2. (**A-C**) Dot plots showing the relationships between components of the 7 analyzed rehab therapies and the mean FM-UE score change from pre-rehabilitation therapy to post-completion follow-up. (**D**) Importance of each feature with respect to FM-UE score, where more positive model error values (x-axis) indicate the linear model fits were *worse* after permuting the data of the associated model feature.

Estimating probability of rehab success

The previous exercise helped delineate that therapies where therapists supervised fewer patients and delivered greater training dosage were linked with greater clinical improvements. However, therapies are not simply sums of their parts: there are interactions between components that can produce non-linear clinical improvements. Therefore, we shifted our analysis focus to the probability of clinical improvement under each therapy. This approach effectively abstracts from the lower-level parameters about each therapy, a point that we return to in the following section. The probability of clinical improvement under each of the potential rehab therapies are plotted in the leftmost panel in figure 3. For this analysis, we simulated hypothetical patient data under each of the therapies, and counted how many simulated patients we would expect to experience an increase in the FM-UE at varying thresholds (see methods).

There is a greater than chance probability for patients to experience small, but meaningful, clinical improvements in any of the examined therapies. For example, the probability that participants experience a change in the FM-UE of 4.2 points from baseline to follow-up was 79.44% ± 5.75% averaged across all 7 rehab therapies. In contrast, the probability to experience larger, more meaningful, clinical improvements is lower. Furthermore, patients attending an in-person rehab therapy (solid lines in Fig. 3A) have a larger probability of treatment success compared to patients attending a remote rehab therapy (dashed lines in Fig. 3A).

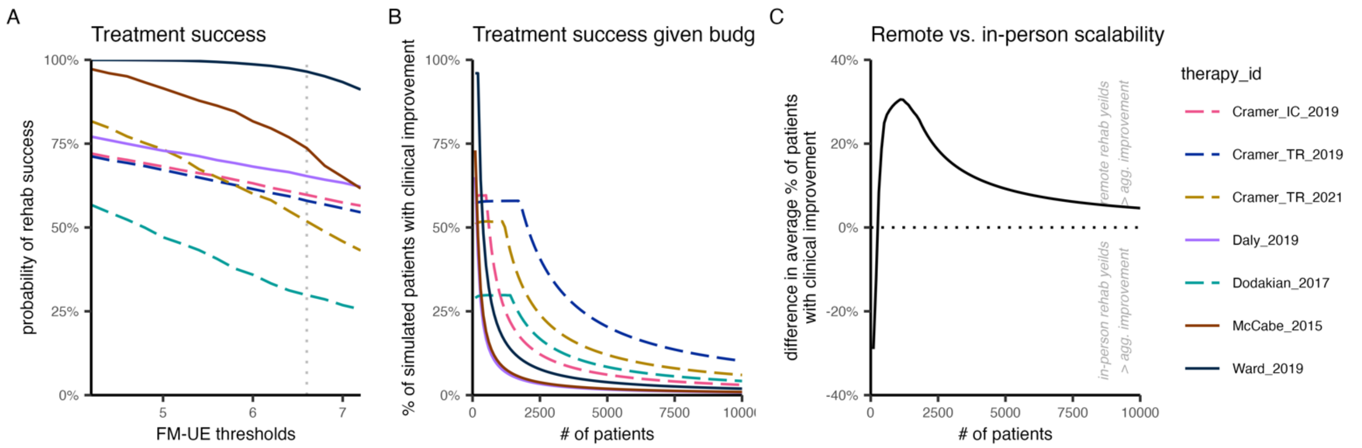

Figure 3. (**A**) The estimated probability of rehab success for each of the 7 therapies. (**B**) The percentage of all patients (treated and not treated) who experience a clinical improvement (a FM-UE score increase of 6.6 – the grey dotted line in the leftmost panel) for a set size of patients needing rehab therapy and given a fixed budget of $1 million USD. In the left and middle panels, therapies with some degree of remote telerehab component are plotted as dashed lines and therapies delivered entirely in-person are plotted as solid lines. (**C**) The average difference between the percentage of patients who experience clinical improvements in remote vs. in-person therapy settings. Values >0 indicate a preference for remote rehab therapies, and vice versa.

Estimating proportion of patients who will experience clinical improvements when scaling-up coverage

Given the results of the previous analysis, it would seem reasonable that an individual patient should attend in-person rehabilitation therapy to maximize their probability of experiencing significant clinical recovery. However, this analysis did not consider the costs associated with delivering these therapies. The effects that costs will have on patient outcomes is more strongly felt when considering clinical outcomes of groups of patients, not individual patients in isolation. Therefore, we then examined the probability of clinical improvements for groups of patients given a fixed therapy budget.

For this analysis, we estimated costs associated with providing rehabilitation therapy to each patient, adhering to the protocols reported in each paper (see methods). These costs considered labour costs for the rehabilitation therapist, equipment costs (predominantly for remote rehabilitation), and travel costs (predominantly for in-person rehabilitation). For example, the estimated cost for one patient to receive the remote telerehab therapy (Cramer et al. 2019) was be approximately $568.54 USD per patient, whereas the in-person therapy (Ward_2019) outlined in Ward, Brander, and Kelly (2019) is estimated to cost nearly 9x more at approximately $4956.75 USD per person. These cost differences arise because of the difference in travel needs and therapist-to-patient ratios in each rehab approach. Given a hypothetical scenario wherein there is a fixed budget of $1 million USD to cover all patient rehab costs, it would be possible to cover the costs of 1758 or 201 patients under the telerehab or in-person therapies previously mentioned, respectively.

Therefore, the potential for each rehab therapy to scale will depend on the cost per patient and the probability of clinical improvement. Given that we anticipate stroke prevalence to increase, we estimated how each rehab therapy could expect to scale as the number of stroke patients needing rehab therapy grew, given a fixed budget of $1 million USD to cover all therapy costs. The results are presented in Fig. 3B. As the number of patients needing treatment increases, the percent of patients who experience a clinical improvement (i.e., achieving an increase in FM-UE of ≥6.6) decreases. This occurs because a fewer proportion of a growing number of patients will get treatment given the cost constraints of a fixed budget. The effect that cost constraints have is greater for in-person (solid lines) compared to remote telerehab therapy options (dashed lines). To better demonstrate this differential effect, the rightmost panel in figure 3 shows the difference in the average percent of patients who we expect to experience clinical improvements in remote telerhab therapies versus in-person therapies. Given our fixed budget, when the number of patients needing treatment is below 200, the better option (in terms of clinical outcomes) would be to treat all patients in-person. When the number of patients needing rehab therapy grows larger than 200, remote telerehab therapies become the preferred option.

Conclusion

We return to the three components important in improving clinical outcomes. Specifically, we noted that a good solution to tackle the growing burden of neurological disorders while improving rehab outcomes in a cost-effective manner will be one that:

1. increases rehab therapy dosage;
2. can deliver rehab therapy with < 1:1 therapist-to-patient ratio;
3. is low cost compared to alternative rehab therapies.

And that an ideal solution will be able to address these three components even as the number of patients increases, all else being equal. We now consider which of the three therapy frameworks (in-person, hybrid, and remote) best meets this assessment criteria.

First, compared to current standards of care, all 7 examined therapies offered relatively high-dose, high-intensity treatment to stroke patients, and therefore all increase the rehab therapy dosage. This increased dosage was associated with high probabilities that a patient in each therapy would achieve clinically significant outcome due to rehab therapy. Second, given the cost associated with higher therapist-to-patient ratios (i.e., greater supervised therapist time), rehab therapies that can deliver clinical improvements using a smaller therapist-to-patient ratio are preferred. Indeed, among the therapies we examined, there was no significant relationship between the therapist-to-patient ratio and the clinical improvement measured in patients (using the FM-UE). In light of this, the remote telerehab therapies, which offered lower therapist-to-patient ratios, are preferrable because they offer clinically significant patient outcomes while keeping labour costs low. Third, when considering additional monetary costs associated with each therapy, the absence of substantial travel costs for remote telerehab therapies means that more patients can be treated with a fixed budget compared to high-dose in-person therapies. more scalable

The results of the analysis indicated that high-dose, high-intensity neurorehabilitation therapies have the potential to deliver meaningful clinical outcomes for stroke patients. Although in-person therapies have a larger probability of treatment success compared to patients attending a remote rehab therapy on an individual level, when considering a population approach, remote therapy shows a greater potential of success for more patients when scaled up.

In conclusion, high-dose, high-intensity neurorehabilitation offers a promising approach to address the growing burden of neurological disorders, specifically in stroke rehabilitation. By implementing a remote, technology-assisted approach, we can improve rehabilitation outcomes within the population in a cost-effective manner with greater scalability while also improving equitable access to needed care.

Limitations & Future Directions

There are several complexities that arise when comparing across rehab therapy approaches. From a technical standpoint, the true time-on-task patients received may be different than that prescribed for each rehabilitation therapy. Many papers did not report completed therapy time, only prescribed time. Assuming the difference between time-on-task and reported therapy times are minimal, the general findings from this case study should remain valid. A similar concern arises when attempting to compare across studies that employed varying exclusion criteria. In the current analysis, we did not substantially control for differences in patient exclusion criteria. Third, our simulation approach assumed that changes in FM-UE scores in each therapy follows a normal distribution. It was not possible to confirm if this assumption was appropriate based solely on the data provided for each therapy in the reviewed papers. Finally, the travel costs were estimated using a “as-the-crow-flies” distance, and therefore reflect the lowest likely costs for treatment travel. Future work could use road networks to estimate travel distances that are more reflective of the realities faced by patients traveling to obtain rehab care.

In this case study, the primary outcome of patient success was measured using the FM-UE. However, patient success is multifaceted and includes social and wellbeing components which were not included in the present analysis. Furthermore, there is social benefit to getting family members and caregivers involved in the treatment plan for patients, as it can provide social systems to encourage patient compliance with rehab treatment. Therefore, one avenue for potential improvement is to incorporate measures of patient adherence, enjoyment, motivation, wellbeing, and social support network into the analytical assessment framework.

Appendix A: Costing Methodology

Labour costs

To estimate the labour cost associated with delivering each therapy, the therapist-to-patient ratios were first computed for each therapy. The ratios were scaled by total therapy time, such that a ratio of 1 indicates a therapist was always supervising an individual patient, whereas a ratio of 0.5 could indicate that a therapist was simultaneously supervising two patients *or* that a therapist supervised only half of the patient's total prescribed therapy time.

Then, the hour labour rate was estimated. Because the analyzed papers did not always specify what type of therapists were provided (e.g., occupational and/or physical rehabilitation therapists), the hourly rate of labour was set to the average hourly wages for occupational ($44.61 USD) and physical rehabilitation therapists ($47.10 USD) in the US for 2023 (US Bureau of Labor Statistics 2023). This yielded an hourly labour cost of $45.86 USD per hour per therapist. Finally, the cost associated to deliver a complete rehabilitation therapy to a single participant was calculated as $h_t * r_t * \$45.86$, where h is the total prescribed therapy time and r is the therapist-to-patient ratio for therapy t.

Equipment costs

Equipment costs were estimated for each rehabilitation therapy. In-person clinical rehabilitation approaches tended to utilize standard exercise equipment like resistance tubing and putty, and so we assumed a per patient cost of $30 USD for the fully in-person therapies. For remote telerehabilitation therapies that utilized more technical equipment like motion controllers, equipment costs were estimated by costing out the individually listed components of for the telerehabilitation therapies, and then adding an additional buffer of $200 USD. We further assumed that the equipment cost for remote telerehabilitation therapies would be equally split across 10 patients, such that a complete bundle of equipment is needed for each set of 10 patients (i.e., equipment can be re-used for new patients). Note that splitting the cost of equipment for remote telerehabilitation therapies across patients will reduce overall costs associated with each therapy and thus influence the relative differences in therapy effectiveness, but the general results hold true regardless of the number of patients that costs are split across.

Travel costs

The changes in the average travel cost will not influence the overall trend of the results presented in this case study, given that changes in travel cost will simply scale all therapy costs by a constant factor (since all therapies involved some amount of travel cost). However, we have opted to provide semi-realistic travel costs in this analysis to demonstrate analytical feasibility.

In this analysis, we employed a toy model to estimating travel costs associated to obtain travel. Specifically, travel costs associated with travel to obtain stroke rehabilitation were estimated using geospatial data for the state of North Dakota. This state was chosen because: 1) it has one of the lowest stroke mortality rates in the United States at 29.4 persons per 100k (US Centers for Disease Control and Prevention 2022) suggesting a higher demand for stroke rehabilitation therapies; and 2) has relatively fewer counties compared to other states, simplifying computational requirements. For each of the 53 counties in North Dakota, we computed the haversine distance (in units of kilometres) from the geographic centre of the county to the nearest of 6 possible hospitals (offering the top-level of stroke services in the state). This resulted in one distance per county, reflecting how far a patient residing in that county would need to travel to attend therapy at the nearest of 6 possible hospitals. Each distance was then doubled to estimate the round-trip distance a patient would have to travel. The cost of this trip was then computed by multiplying the roundtrip distance by the in-state travel reimbursement rate of $0.4071 USD (per km). Finally, to obtain a population-weighted average of all costed trips was computed, yielding a single travel cost estimate of $52.50 USD.

This cost estimate reflects what a randomly selected resident of North Dakota would likely need to pay per roundtrip travel to the nearest of 6 possible facilities. The total travel costs for each therapy were then calculated as the number of in-person sessions multiplied by the average roundtrip cost estimate of $52.50 USD. Although fully remote telerehabilitation therapies do not require patients to travel to a clinic, there is a requirement that the rehabilitation equipment is delivered to the patient's home. Therefore, for we included the travel costs (one roundtrip) associated with equipment delivery for fully remote telerehabilitation therapies (Dodakian et al. 2017; Cramer et al. 2019, 2020).

This approach can be scaled up to include other geographic regions, potential treatment locations, and the integration of travel via road networks (see Limitations & Future Directions).

Appendix B: Supplementary Figures

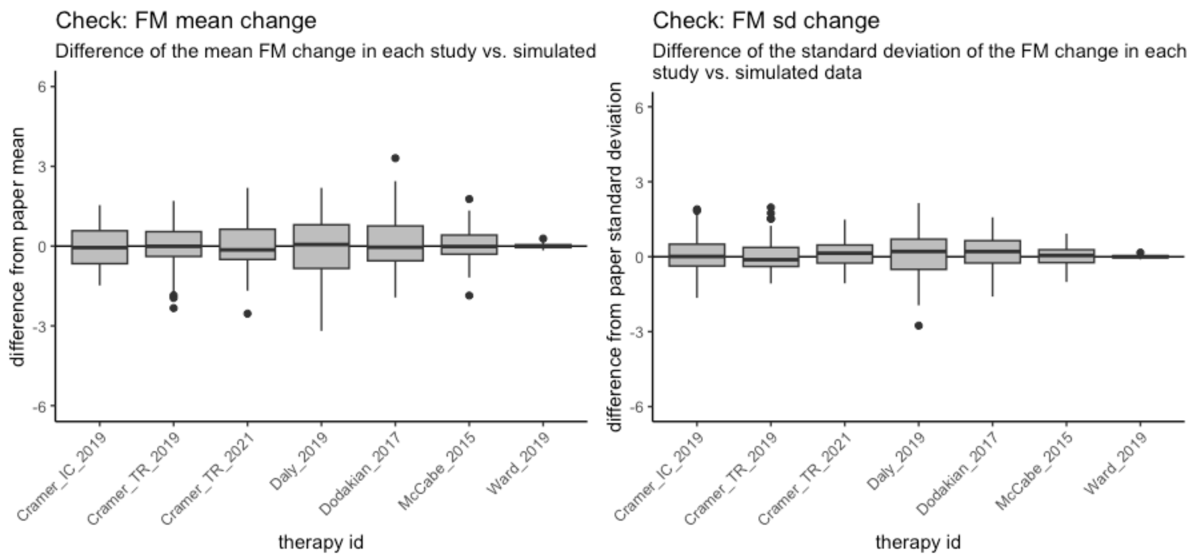

Figure S1. The means (left) and standard deviations (right) of each batch of simulated patients per therapy are plotted as a function of how far they differ from the report values in the respective papers.

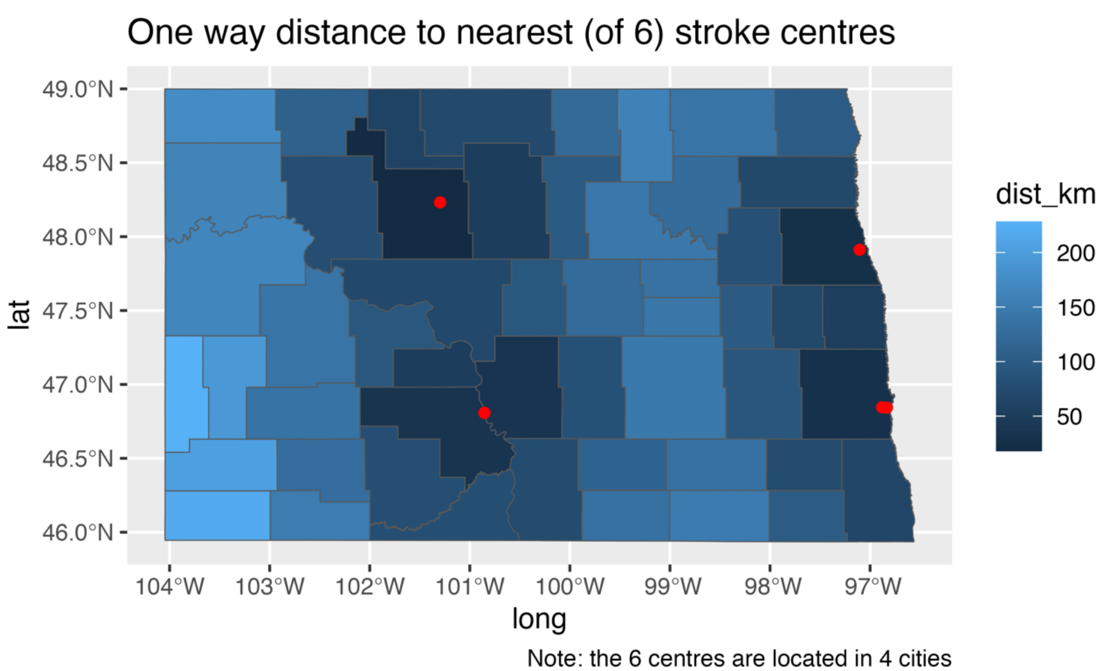

Figure S2. Computed haversine distance to the nearest (of 6) stroke centres in North Dakota. The colour of each county (53 counties) reflects the haversine distance (in km) from the county's geometric centroid to the nearest stroke centre. The 6 stroke centres are located in 4 cities, with centres in the same city being located very near to each other.

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