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GAIT REHAB ADAPTIVE MACHINE: DESIGN OF GRAM, A WALKING LINKAGE POWERED WHEELCHAIR FOR LOWER BODY THERAPY AND ASSISTANCE

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BACKGROUND

Nearly half of individuals with stroke experience some form of long-term disability and stroke is one of the main causes of wheelchair use in the United States [1]. Early rehabilitation in the acute phase of stroke has been shown critical to promoting motor plasticity and patient outcomes. However, research shows that only 32% of the time during inpatient rehabilitation is spent in active therapy, while the rest of the time is spent on other activities around the ward [2]. For walking impairment, it is especially important for patients to experience similar force loading and practice the patterning of gait in order to recover [3]. However, in a typical therapy session focused on gait rehabilitation patients only will take about 300 steps on average. This is far below what has been thought needed for humans to learn how to walk [4].

Currently, technology options to provide therapy include overhead treadmill systems like the Lokomat or exoskeletons like the ReWalk, but these systems have considerable cost, complexity, and bulk, limiting the number of clinics that can obtain them for patients [5]. Likewise, attempts to add therapy to wheelchairs for stroke patients have been mostly limited to pedal devices [6]. These devices also have limitations because pedaling does not provide a similar muscle patterning to walking and some devices do not utilize the affected side in their control [7]. This second type of device does not promote use of the impaired limb, which can further disuse and impairment.

This paper details the design and feasibility evaluation of a novel wheelchair called GRAM (Gait Rehab Adaptive Machine) for potential application in walking impairment recovery. First, the theory for using a six-bar linkage that simulates the trajectory of human gait as a propulsion mechanism for a wheelchair is discussed. Next, feasibility in an unimpaired subject in a distance test analogous to the 10-meter test used in physical therapy is explored [8]. Potential implications for rehabilitation and future work are discussed.

FIGURE 1. The nonimpaired subject in GRAM. A six-bar mechanism guides the leg in a walking trajectory, which couples to the wheelchair via a gearing system to provide propulsion with each repetition.

METHODS

A. Design Rationale

GRAM is designed to reduce the complexity associated with other leg therapy devices while providing the necessary practice with a relevant walking-like motion to be effective. Thus, a single degree of freedom six-bar linkage was used, so unlike other designs, only a single actuator would be required to provide assistance if needed. Likewise, this design reduces time to therapy since no transfers are required, increasing safety and therapy opportunity. The device can operate in two modes, either the actuator can drive the leg passively, or the patient drives the linkage with or without assistance from the actuator based on their ability level. Thus, the device can adapt to the level of the patient, providing gradable challenge. The linkage was designed by collecting motion capture data of the author walking straight ahead on a 3-meter-long flat hallway at a self-selected walking pace. These trajectories were then used to solve for the linkage synthesis, further details which can be found in [9]. See Fig 1.

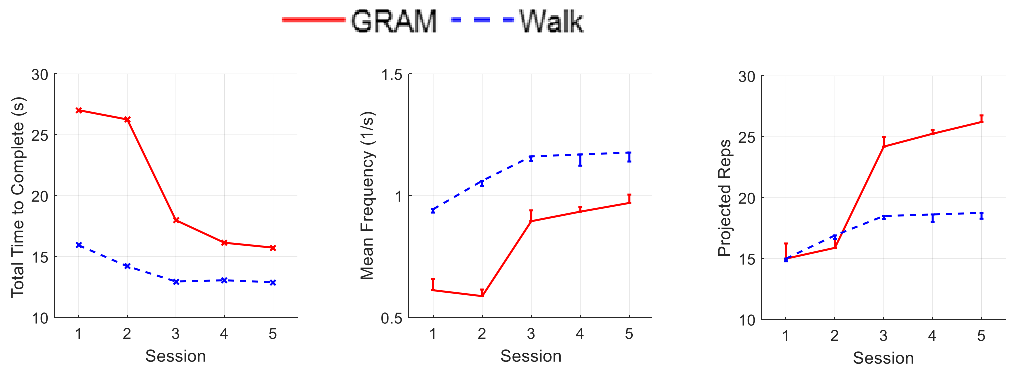

FIGURE 2. **Left:** There was a significant change in the time to complete the 15 repetitions over the 5 sessions which resulted in a significant increase of repetition frequency (**Middle)** that translated to an almost doubling of expected repetitions by the last study day (**Right)**.

B. Experimental Setup

Prior work informed the study methodology [10]. An unimpaired female (age = 25 years) drove a wheelchair outfitted with a single GRAM unit on the right side with their right leg for 15 repetitions (about 0.6 meters distance traveled per repetition, for a total distance of about 9 meters). During this test, the contralateral arm remained in the subject's lap and their contralateral leg was on the wheelchair's footrest. The subject drove GRAM with their own leg power and no assistance. The subject then walked for the same repetitions (15 repetitions of walking, where a repetition was counted as a heel strike of their right foot) for the same stride length as GRAM (0.6 meters) per repetition to provide walking data as a comparison for some of the analyses. In both tasks, the goal was to go as fast as possible, and in the case of the walking task, to do so without running. This test served as an analogy to the 10-meter walk test used in physical therapy to assess gait. Lap times were recorded with a stopwatch application (Apple iPhone native app), where each new lap began when the subject's right heel struck the ground or when the mechanism returned to its starting position. A chest heart rate belt (Polar H10 Wireless Heartrate Monitor) was worn during the study to measure resting and peak heart rates. Before each experiment, the subject sat still in a chair for 30 seconds to assess a resting baseline, then performed the test in GRAM. They took a 5-minute break, sitting still in a chair, to allow heart rate to return to normal, and then performed the same distance walking. The subject did five sessions total, one session per day. The subject did three sessions in a row, took a two-day break, then returned for the remaining two sessions.

C. Data Analysis

For each repetition, mean velocity was calculated by dividing repetition time over distance (0.6 meters). Frequency was calculated as the inverse of repetition time. Total projected repetitions were extrapolated by multiplying the frequency of repetition by the time it took to perform the test the first day. Within-day improvement was calculated by subtracting the velocity of the last repetition from the first repetition. Between-day improvement was calculated as the difference between the velocities of the first repetition of the day subtracted from the last repetition of the prior day. Positive values in either within or between-day improvement corresponded to performance improvements. Learning rate was assessed via a power curve fit with MATLAB's "fit" function (curve fit option 'power1') to the subject's time per repetition data over the five sessions with

$$T = BN^{-\alpha} \quad (1)$$

Where B, α are constants and α is the learning rate [11]. B is the baseline, or first repetition time and N is the amount of trials T is the time to finish the task.

Physiological cost index (PCI), an equation that relates the subject's efficiency of locomotion was calculated as:

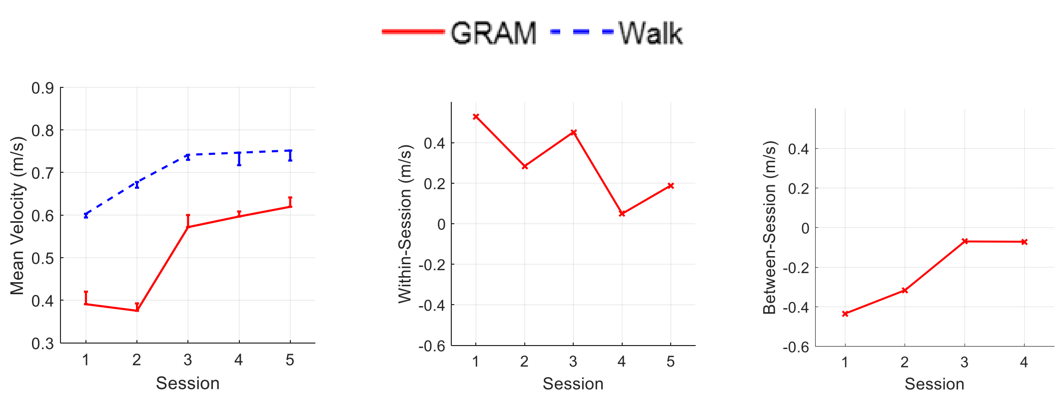

FIGURE 3. **Left:** There was a significant change in velocity between groups and over sessions. **Middle:** Most of their speed improvement for GRAM was within the session, as opposed to between **(Right)**

$$PCI = \left(\frac{Ending\ HeartRate - Starting\ HeartRate}{Velocity}\right) \quad (2)$$

Change in heart rate was calculated by subtracting the peak heart rate during exercise from the average value from the baseline measurement for each day. The groups were compared using a linear model to ascertain differences in time to complete repetition, overground velocity, PCI, frequency of repetitions, projected repetitions and within and between-day improvements. There were four terms in this model, a term for day, group (GRAM or natural walking), a term for repetition (1-15 for the 15 repetitions done per day), and an interaction term between-day and group was used. For change in heart rate, a second linear model was used that had three terms, day, group and an interaction term between-day and group. T-tests were used for some comparisons. Error bars are standard error.

RESULTS

A. Learning GRAM

To compare the difficulty of learning GRAM, a single subject's performance using GRAM versus their performance in a walking task as a baseline was quantified. The subject improved their time to complete 15 repetitions as computed by the linear model for the group, and the interaction term ($p<0.001$, $p<0.001$). On the first session, it took the subject about 27 seconds to perform 15 repetitions in GRAM. On the last day, it took 15.7 seconds to do this with GRAM (Fig 2, Left).

GRAM reported a learning rate of α=0.36. The learning rate of GRAM was not statistically different than the mean rate found in a sampling of classic learning experiments in unimpaired subjects (α= 0.28 ± 0.16 SD; unpaired t-test, p =0.68) [12].

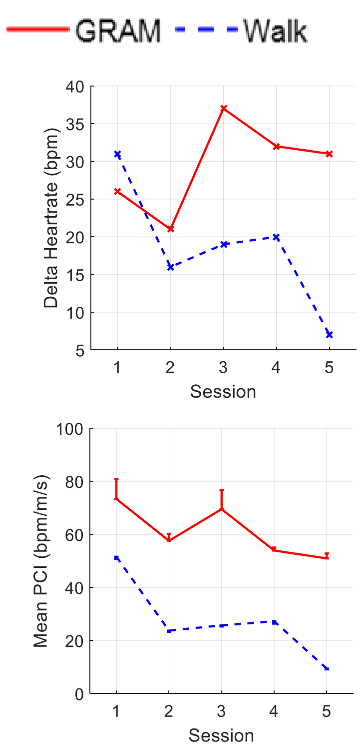

FIGURE 4. **Top:** There was a significant change in heart rate and (**Bottom**) PCI between groups.

The group, day, interaction and repetition term of the velocity curves were significantly different from each other (linear model, $p<0.001$, $p<0.001$, p=0.002, p=0.01). The mean speed achieved during training increased significantly for both groups across the five sessions of the study. GRAM was 35 % slower than the walking task the first day, but by the last day, GRAM was only 17.6% slower (Fig 3, Left). The speeds of GRAM fall in the range reported for manual wheelchair use of 0.48-0.8 m/s [13].

B. Between and Within-day Improvement

The linear model analysis showed significance for the repetition term which represented within-day improvement ($p<0.001$). This suggests GRAM showed velocity improvement mostly within the session. (Fig 3 Middle).

A similar analysis was performed on the between-day improvement. Here, the linear model also showed significance for the day term which represented between-day improvement, (p =0.001). GRAM started each day with a lower velocity then it finished the prior day with, suggesting most of the improvement occurred within the session (Fig 3 Right).

C. Frequency of Repetitions and Projected Repetitions

The rate of repetition was significantly different between groups and increased over days and for each group (Fig 2, Middle linear model, p <0.001, $p<0.001$). Similarly, the linear model showed there was significance for the interaction term (p =0.002) and the repetition term (p=0.01). By the end of the study, GRAM had a frequency of 0.9 Hz while the walking task had a frequency of 1.2 Hz. The projected repetitions per day were significantly different between groups, over days, and for the interaction and repetition terms (Fig 2, right, linear model, p <0.001, $p<0.001$ p=0.002, p=0.01). GRAM started with a repetition count of 15 reps on the first day and ended with a projected repetition count of 26 repetitions.

D. Changes in Heart Rate and Physiological Cost Index

As demonstrated by the linear model, there was not a significant difference for the group or day term, but the interaction term trended to significance for the change in heart rate for both groups (p=0.4, p=0.8, p=0.09) The change in heart rate for the last session was 31 bpm for using GRAM for this subject (Fig 4, Top).

PCI was significantly different between groups and over days but was not significantly different for the interaction term (Fig 4, Bottom, linear model p <0.001, p< 0.001, p =0.34). PCI was significantly different for the repetition term (p=0.02). On the first session and last session, GRAM had a PCI that was 143.7 bpm/m/s and 99.8 bpm/m/s. The walking task had a PCI of 101 bpm/m/s on the first day and on the last day a PCI of versus the walking task a PCI of 18.5 bpm/m/s ± 9.9 SD.

INTERPRETATION

This paper showed the feasibility of GRAM in a case study with a nonimpaired subject. The main results were that 1) the design approach to GRAM is feasible for wheelchair propulsion, and GRAM can move at speeds comparable to the range reported in the literature for manual wheelchair use. 2)

GRAM had higher physiological metrics in terms of repetition frequency and projected reps than the control. GRAM also had a higher PCI metric despite slower speeds or was less efficient than the walking task, and for this subject, 3) required practice within the session to improve velocities.

A. Overground Speeds and Physiological Efficiency

GRAM was slower than the walking task, and by the end of the study still lagged a significant 17.5 % behind in over ground velocities. However, the speed reported on the third day, 0.57 m/s, is in the range of values reported for overground manual wheelchair speeds of 0.48-0.8 m/s meaning its performance is comparable to these devices, at least for this subject.

Similarly, GRAM had a significantly larger change in PCI. The differences in PCI decreased as time went on in the study, suggesting part of the exertion came from learning how to coordinate GRAM. The subject also significantly increased their repetition count over time for both groups, leading to a 1.7 increase of projected repetitions from the first day with GRAM, compared to a 1.25 increase from the walking task.

B. Learning How to Operate GRAM

The learning rate of GRAM was not significantly different from the mean of learning rates reported for unimpaired subjects from [12]. Similarly, the subject was able to increase their speed in GRAM about 36% over 5 days, compared to their increase of walking speeds of about 15% over the study. This suggests that GRAM, like walking, is a motor skill requiring time to learn.

Interestingly, most of the improvement for GRAM happened within the session for this subject which would suggest the motor task was not complex since sleep was not required to consolidate learning [14]. One possibility is that GRAM could have over fatigued the subject, and an experimental protocol that allowed a day off between sessions for the leg muscles to completely recover may have unmasked between session learning. Based on these results prolonged training sessions are recommended to master GRAM at least for this subject.

C. Study Limitations and Further Research

The main limitation of this work is the small sample size. More participants of various age and fitness level are needed to fully assess the difficulty in learning GRAM and these results are strictly generalizable to only this subject. Furthermore, the study would need to be extended to individuals with leg impairment to investigate the potential benefits of GRAM.

In the context of stroke rehabilitation, GRAM could potentially serve to promote greater use of the impaired limb, as by the last day the subject nearly doubled their projected repetitions for their brief bout of exercise. Similarly, lower PCI is desirable for rehabilitation since cardiopulmonary exercise elicits motor recovery after stroke [15]. For example, this subject had a mean change in heart rate of 29.4 bpm, which demonstrates the feasibility of GRAM as an exercise device since it put the subject in their target zone for cardiovascular exercise. Further, GRAM was a task that could be learned and improved upon within the session, providing a way to motivate the individual and minimize frustration. This could possibly increase exercise compliance, a core issue in rehabilitation. Further studies should investigate the potential of GRAM to play a key role in increasing therapy accessibility and mobility to disabled individuals like those with stroke.

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