Comparison of User Metabolic Efficiency between Traditional and Spring Assisted Leveraged Freedom Chair Models

by

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Abstract

Tests were performed to determine how the use of an elastic energy storage mechanism on the Leveraged Freedom Chair would affect the rider's metabolic efficiency. For this test, elastic bands were attached to the levers, and the rider's heart rate was recorded as he rode multiple lengths of a field in a timed trial, in both the spring assisted LFC and the traditional LFC. Efficiency in the spring assisted LFC, normalized by the efficiency measured on the traditional chair, was found to be $\epsilon_n = .684$. This may indicate that there is a higher metabolic cost associated with pulling than with pushing in the LFC. The lower efficiency may also have resulted from the arbitrary choice of spring constant, as well as viscoelastic losses in the elastic bands. The user experienced much higher fatigue in the traditional LFC, primarily in the latter half of the 887 meter course, suggesting that in spite of the current decreases in efficiency, the spring system could add value by allowing users the option to travel longer distances.

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Chapter 1

Introduction

1.1 Motivation

In poorer nations, where handicap accessible infrastructure is unavailable, many wheelchair users are limited to using their chair as their sole means of transportation for long and short distances alike. Conventional, non-powered wheelchairs are limited in their range of travel to surfaces that are relatively smooth. In communities where unpaved roads are common, this severely limits users' ability to support their families and otherwise function normally.

The Leveraged Freedom Chair(LFC) is a mobility aid that was developed at MIT by students and faculty to address this issue, initially designed for wheelchair users in developing countries.

The product proved very successful, and has increased mobility for hundreds of users around the world by adding to the number of types of crossable surfaces. To build on this innovation, some researchers have begun to explore the possibility of incorporating an elastic energy storage mechanism as a means of enhancing users' ability to travel long distances in the chair.

In this study, tests were performed to determine whether or not a user's metabolic efficiency while using the LFC could be enhanced by using a spring to distribute the work of propulsion over different muscle groups.

Chapter 2

Background

2.1 The Leveraged Freedom Chair

The LFC is an all-terrain alternative to traditional pushrim wheelchairs, which employs levers for propulsion. This enables users to traverse relatively rough and bumpy terrain, which would be exceedingly difficult in a pushrim wheelchair. The LFC was further designed to be lightweight, durable, narrow enough to fit through a doorway, and very inexpensive.

By providing a long lever arm, the LFC allows users to apply a greater input torque to the drivetrain, which itself is geared up, allowing them to "benchpress" their way across rough terrain that was previously inaccessible. A second key attribute of the LFC is the large front caster wheel, which is better for crossing over obstacles than the pairs of smaller wheels found on most wheelchairs.

The LFC was found to be so effective that a model was later developed for use in the United States, finding its market among wheelchair users seeking an enhanced range of outdoor activity and recreation.

2.2 Prior Work

Herr and Langman demonstrated that during physical activity, metabolic efficiency may be increased by augmenting human capacity through the use of elastic energy

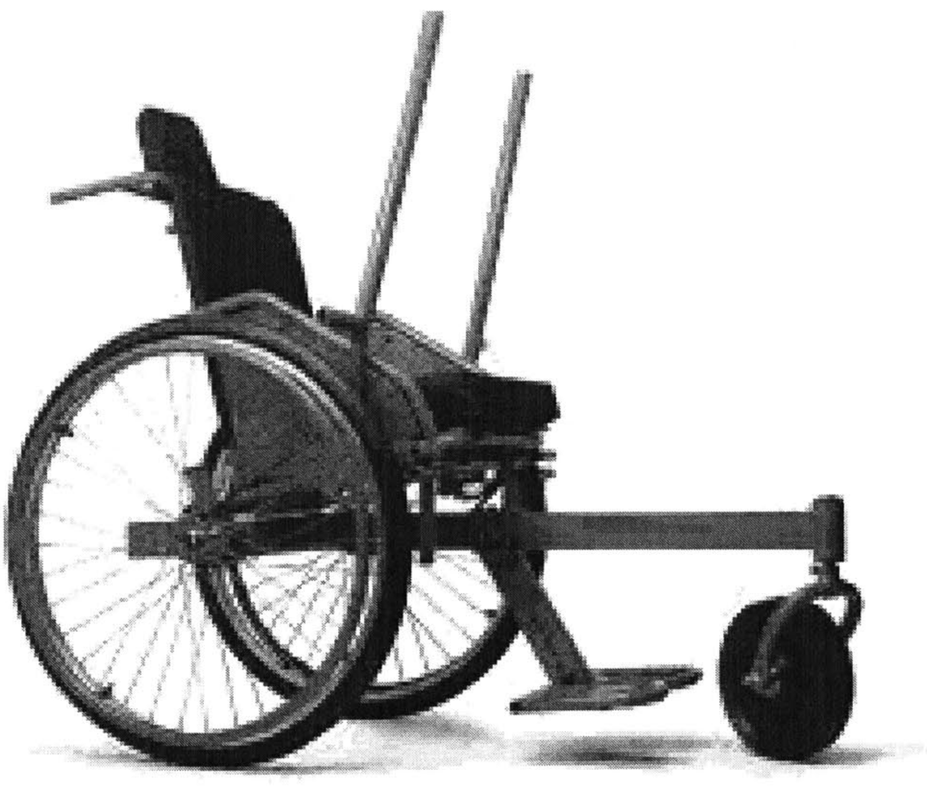

Figure 2-1: LFC model designed for the developing world.

Figure 2-2: The "Freedom Chair"- an LFC model designed for the U.S.

storage mechanisms[1]. If an exercise primarily uses a particular set of muscle groups, then elastic energy storage (i.e. Hookean springs) can improve efficiency by distributing the work done so that previously unused muscles might share the load.

This principle was applied to the LFC in earlier work by Cho et al., who performed an experiment integrating elastic energy storage mechanisms into the chair. A theoretical optimization was performed to determine the ideal spring constant for metabolic efficiency. However, VO_2 data from these experiments revealed surprising decreases in metabolic efficiency, even when the optimum calculated spring constant was used. In this study, the efficiency, ϵ, was defined as the muscle work to extend and flex one arm during each cycle, W_{arm}, divided by the metabolic cost to perform the work [2],

$$\epsilon = \frac{W_{arm}}{E_{met}} \tag{2.1}$$

2.3 A Simplified Model

Above, W_{arm} was assumed to be constant with or without the spring-assist mechanism in their analysis. A distribution-moment model was applied to determine E_{met}. As a simpler alternative, we may express efficiency as

$$\epsilon = \frac{W_{path}}{E_{met}} \tag{2.2}$$

where W_{path} represents work done to travel some distance x. W_{path} is given by

$$W_{path} = \int F_{roll} dx \tag{2.3}$$

where rolling resistance F_{roll} is the net force from kinetic friction, soil deformation, air drag, etc. If we now assume that these forces remain constant during movement at constant velocity, then we may assume that two wheelchairs of equal weight and shape require the same W_{path} to travel across a particular stretch of earth given identical conditions. To determine E_{met}, we may use heart rate as a proxy for human power output, P_{out}, which is energy over time. It was shown in one study that in performance cyclists, below a certain personal threshold[1], the relationship between heart rate and power output is effectively linear [3]. If we adopt this assumption, we may now express human power output as

$$P_{out} = \alpha(HR - HR_{rest})^n \tag{2.4}$$

with $n = 1$ for values of P_{out} below that personal threshold. We may then obtain E_{met} by integrating P_{out} over time. This means that heart rate integrated over time is proportional to E_{met}, which is

$$E_{met} = \alpha \int (HR - HR_{rest})dt \tag{2.5}$$

for $n = 1$.

[1]This personal threshold represents the exercise intensity at which the person's metabolic response changes from aerobic to anaerobic.

Chapter 3

Experimental Procedure

3.1 Spring Mechanism Integration

To test the elastic energy storage concept on the LFC, a traditional Leveraged Freedom Chair (US model, 18" seat width) was retrofitted with levers that extend below their own axis of rotation. Elastic exercise bands were attached by cables to the bottoms of the levers and affixed at their opposite ends to the backrest, such that rotating the lever backwards would stretch the bands. This setup causes the springs to resist the user during the reverse stroke, while augmenting the user's applied force during the forward stroke. The cables ran around pulleys to reduce friction. For each lever, two elastic bands were used in parallel as the springs. The red band had a spring constant of approximately $395N/m$, and the tan band had a spring constant of about $1133N/m$, for a combined spring constant of about $1528N/m$. Limitations of this setup include the fact that the resistance provided by the exercise bands inhibits the user's ability to apply the brakes, since the brakes on each wheel are applied by pulling the lever into its fully upright position. Turning is best accomplished by applying brakes to one wheel, which meant that turning was rather irregular without the ability to brake.

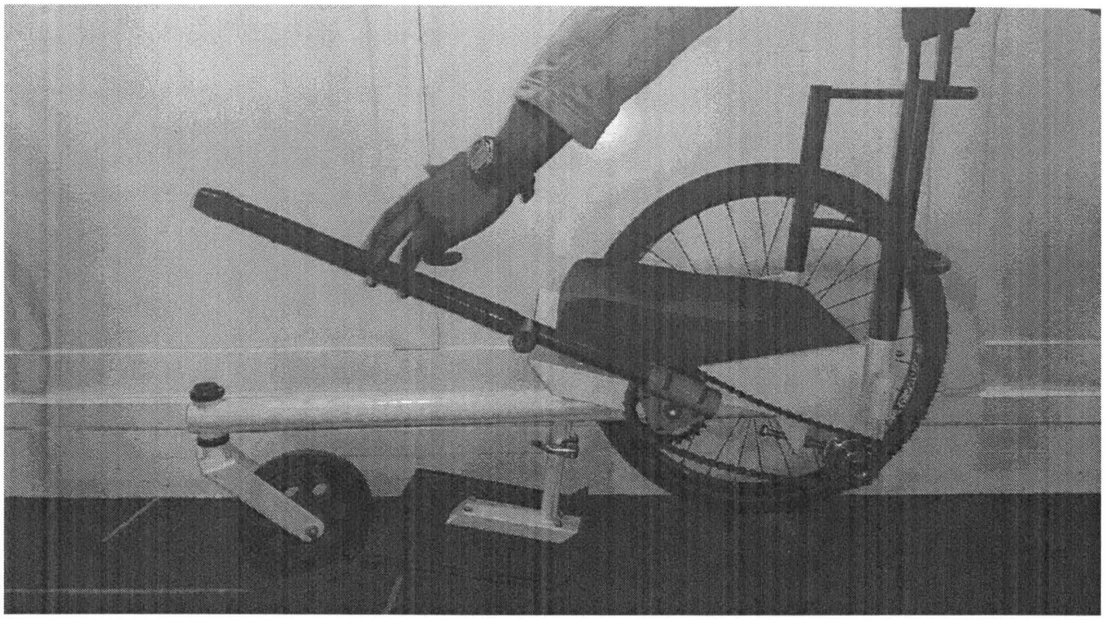

Figure 3-1: Traditional LFC (US model, 16" seat width) with one wheel removed to expose gear train; lever in downward position

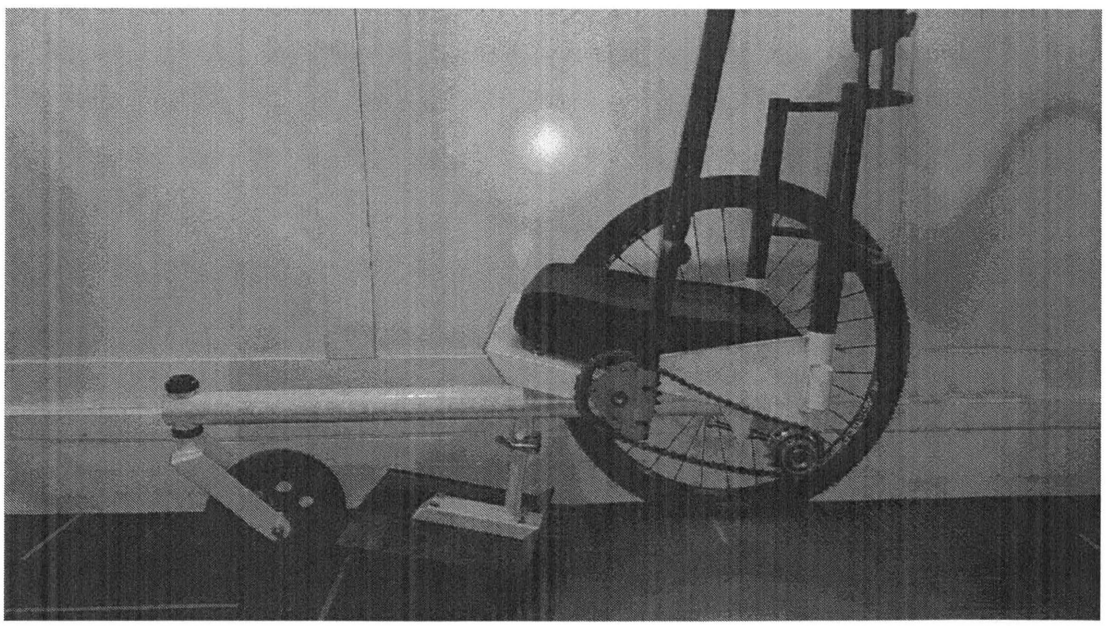

Figure 3-2: Traditional LFC; lever in upright position (this is also the braking position)

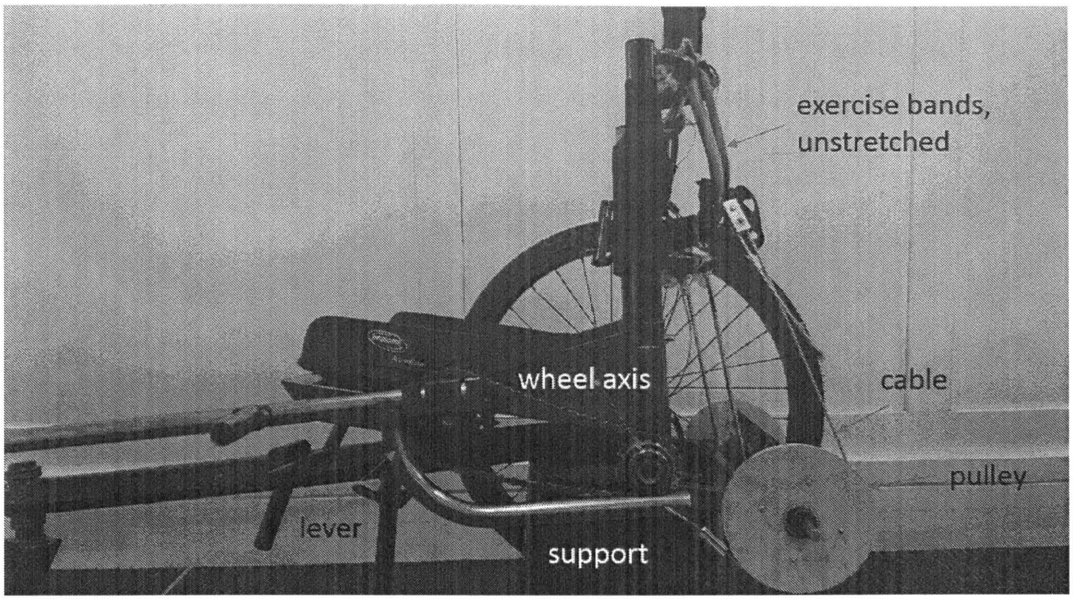

Figure 3-3: Spring assisted LFC (US model, 18" seat width) with one wheel removed; lever in downward position, springs unloaded (the black cylinder beneath the wheel axis is used as a support for display purposes only and is not part of the prototype)

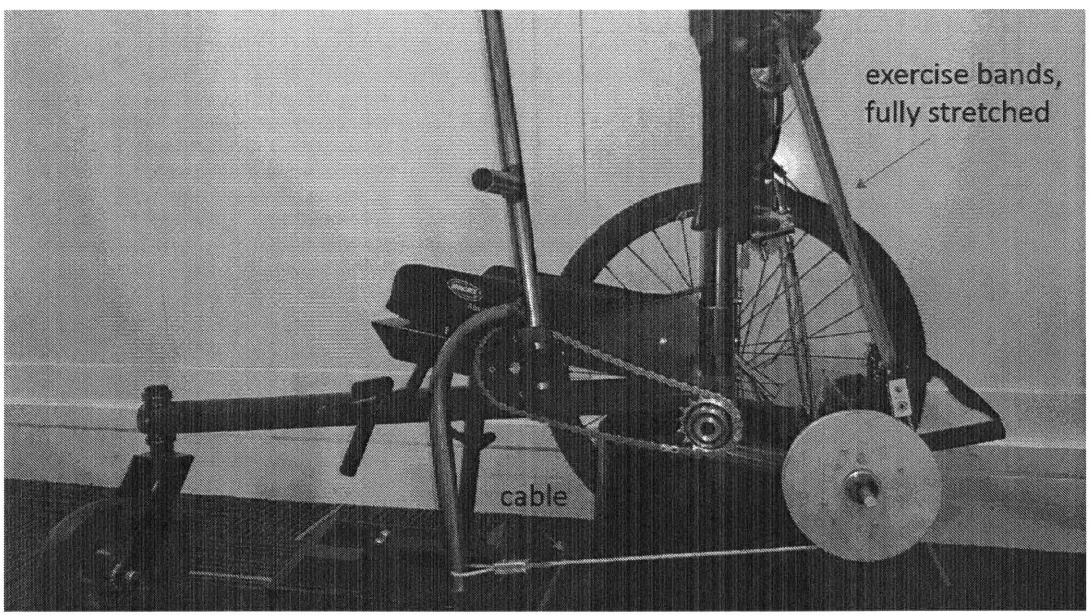

Figure 3-4: Spring assisted LFC; lever in upright position, springs fully loaded. Force is required to maintain the lever in this upright position, which negatively impacts the user's ability to brake.

3.2 Time Trials

To compare the efficiency of the traditional LFC to the spring assisted LFC, a test subject (the author) was timed while riding the spring assisted model across the length of 2 consecutive soccer fields with 2-3 inches of grass, followed by the same test performed with a traditional LFC. For the traditional LFC test, the spring assist mechanism was disengaged, but not removed, so as to keep the chair at a constant weight, thereby maintaining a constant F_{roll} for the two tests. Grass was chosen as the testing surface because it provides a higher rolling resistance than flat ground, due to the force required to deform the soil. A spring assist system is, in one sense, a way of allowing a user to apply a higher input force to the pushing motion, and is therefore more appropriate for situations where high rolling resistance demands a higher torque. Each run consisted of 2 round-trip laps across the fields, a total distance of approximately 887 meters. The subject's heart rate over time was recorded using a POLAR Heart Rate Sensor, model H1, which was worn on the chest, fixed by an elastic strap. A read-out display was worn on the wrist, and was used for real-time feedback, allowing the user to adjust his pace and effort, so as to maintain a heart rate of about 120 bpm (thereby freezing one of the variables). The subject was a 20 year old male weighing 91.3 kg, and the chair weighed 26.1 kg for a combined mass of 117.4 kg.[1]

[1] The subject's mass was measured 1 day prior to the test, so the mass given is only approximate.

Chapter 4

Results

4.1 Experimental Data

The test with the traditional LFC yielded a mean heart rate of 107 bpm, and the course was completed in 13 mins, 20 seconds. The test with the spring assisted LFC yielded a mean heart rate 121 bpm, and was completed in 15 mins, 35 seconds. If the efficiency of the traditional LFC is used as a baseline, ϵ_0, then we may define a normalized efficiency

$$\epsilon_n = \frac{\epsilon}{\epsilon_0}$$

such that the traditional LFC would have ϵ_n =1. Since ϵ is given by equation (2.4), we can express ϵ_n as

$$\epsilon_n = \frac{\left[\frac{W_{path}}{E_{met}}\right]_{SpringAssist}}{\left[\frac{W_{path}}{E_{met}}\right]_0}$$

and canceling W_{path}, we may further substitute equation (2.5) to give

$$\epsilon_n = \frac{\int HR_0 dt - HR_{rest}t}{\int HR_{SA} dt - HR_{rest}t}$$

where the constant α has been removed, since it appears in both numerator and denominator.

Resting heart rate was measured to be 66 bpm in the spring assisted LFC test, and 63 bpm in the traditional LFC test. Heart rate integrated over time was found by multiplying the average heart rate by the total time for each trial. For the traditional test, this gave 8.56×10^4 $bpm * s$, and for the spring assisted test it gave 1.13×10^5 $bpm * s$. The spring assisted LFC therefore had $\epsilon_n = .684$, nearly 30 percent less efficient than the traditional LFC.

4.2 Discussion

The spring-assisted LFC's failure to improve efficiency may be partly due the use of an arbitrarily chosen spring constant. Results from Cho et al. suggest that the spring constant for maximum efficiency should increase almost linearly with rolling resistance[2]. The exercise bands might also exhibit slightly viscoelastic behavior, which would further affect efficiency, as stress relaxation reduces the effective stiffness of the bands. Stress relaxation has a damping effect, and this energy loss means that the bands will not return the same amount of energy that was expended in stretching them. Tests may further be performed to estimate losses due to friction in the pulley. An additional reason for the lower efficiency may be that the pushing motion in the LFC simply has a lower metabolic cost than pulling in the LFC.

The average heart rates were a surprising characteristic of the trials. The expectation was that for either test, 120 bpm would correspond to a comfortable level of exertion. In the spring assisted LFC, the user quickly did find a natural rhythm that corresponded to heart rate of 120 bpm. In the traditional LFC, however, a comfortable rhythm and level of exertion actually yielded a heart rate of 107 bpm, and the user found that significantly higher exertion was required to increase heart rate to 120 bpm. One would suppose that heart rate would respond to both an increase in stroke frequency and to an increase in the force applied during the stroke (i.e. lever velocity), and while this was true, the subject observed that heart rate seemed to respond more to the frequency of strokes than to force applied per stroke. The subject found that reaching 120 bpm in the traditional LFC required an uncomfortably high stroke frequency. At a comfortable frequency in the traditional LFC, it required a very strong applied force to reach 120 bpm.

The differences in average heart rate value (i.e. the most comfortable rate) could be related to the nature of the stroke in each of the two LFC versions. In the spring-assisted LFC, the application of force was spread more evenly throughout each cycle. By contrast, in the traditional LFC, the profile of user force input, if plotted against time, would be more similar to a sinusoid or a sawtooth function. Ultimately, in the traditional LFC, due to fatigue, the frequency of strokes had to decrease significantly over time. The fatigue effect was significant enough that the user had to pause movement entirely at several different points in the trial.

The difference in fatigue level might be explained by the fact that in the spring-assisted LFC, the energy expended in moving the chair 887 meters was divided between two primary muscle groups (biceps and triceps), whereas in the Traditional LFC, all that energy was expended through one muscle group (triceps). Additionally, the spring assisted LFC enabled smaller peak loads in the pushing motion. Because the spring contributed to the forward push, less force was required to keep a frequency corresponding to 120 bpm. By contrast, in the traditional LFC, because a high frequency was required to keep up the heart rate, there was less resting time for triceps in between high peak loads. Another possible reason for reduced fatigue in the spring assisted version was that the distribution of force between different muscle groups allowed the user to "alternate" between them (primarily biceps and triceps). The user could preferentially exert one group more when the other became exhausted or sore. This feature of the spring assist mechanism may make it valuable for enhancing LFC usability, especially given existing wheelchair propulsion research [3, 4, 5] that suggests that both aerobic and anaerobic fitness may play a significant role in wheelchair locomotion.

It should be noted that the attempt to maintain a constant heart rate did create a somewhat artificial constraint that does not necessarily reflect the typical use of the chair. In normal use, a rider has no obligation to maintain a certain stroke frequency. The result still stands, however, that using the triceps to do the entire work of locomotion over a given distance will cause greater fatigue than distributing that work between the triceps and biceps. Another important note is that although there is a relationship between heart rate and metabolic power output, they are not perfectly correlated. It may be worthwhile to conduct future tests to determine whether or not decreased metabolic effort corresponds to decreased fatigue when using the springs.

Chapter 5

Conclusion

Tests were performed to determine whether or not LFC users' metabolic efficiency could be enhanced by incorporating a spring to distribute the application of force over different muscle groups. The spring assisted LFC was compared to the traditional LFC in a time trial over a defined course. The spring assisted LFC efficiency, normalized by the traditional LFC's efficiency, was $\epsilon_n = .684$, possibly indicating that the metabolic cost of doing some quantity of work in the LFC by pulling is far greater than the cost of doing it by pushing. Lower efficiency may have also resulted from the stiffness of the chosen elastic bands, as well as viscoelastic losses in the bands. The traditional LFC trial revealed a much higher fatigue level over long distances, suggesting that perhaps the assistance provided by the springs may still be of value for increasing the distances users can reasonably travel. Future work would entail design of a mechanism to easily engage or disengage the spring system, as well as mechanisms to enable braking while the spring system is in use. Additional design work would be necessary to make a spring assisted LFC which was comparable to the traditional LFC in mechanical efficiency and in user metabolic efficiency, and further tests could be done to explore the relationship between metabolic exertion and fatigue.

Appendix A

Additional Tests

An earlier test was performed using a Vernier Exercise Heart Rate Monitor, Model EHR-BTA. The data collection tool used was capable of recording and displaying the user's heart rate over time; results are shown below in Figures A-1 and A-2. Data were collected at a sample rate of 25 Hz. The subject tried using a metronome to maintain a steady stroke frequency of 40 strokes per minute. The test with the traditional LFC yielded a mean heart rate of 112.90 bpm with a standard deviation of 17.06 bpm, and the course was completed in 1126.48 seconds. The test with the spring assisted LFC yielded a mean heart rate 139.86 bpm with a standard deviation 24.79 bpm, and was completed in 1268.92 seconds. Because the frequency of the strokes was kept approximately constant, the overall run times were comparable. Resting heart rate was measured in a later test to be 55 bpm. In the traditional LFC test, heart rate integrated over time was 1.25×10^5 $bpm * s$, and for the spring assisted test it was 1.75×10^5 $bpm * s$. The spring assisted LFC therefore would have had $\epsilon_n = .603$. It was later discovered, however, that interference was causing the monitor to give faulty readings, resulting in erroneous spikes and irregularity in the data. Following this discovery, the tests were redone using the other monitor, yielding the data presented in the text.

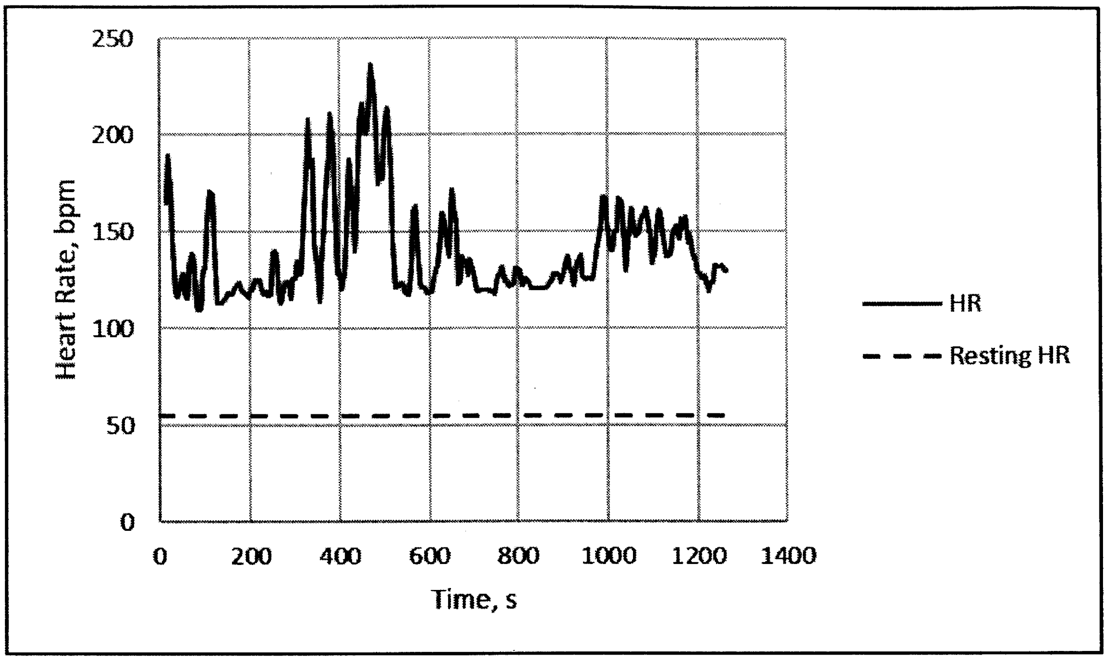

Figure A-1: Heart rate vs time for spring assisted LFC over 2 roundtrip laps along 2 adjacent soccer fields, interference causes unusual spikes, especially between $t = 320$ s and $t = 520$ s.

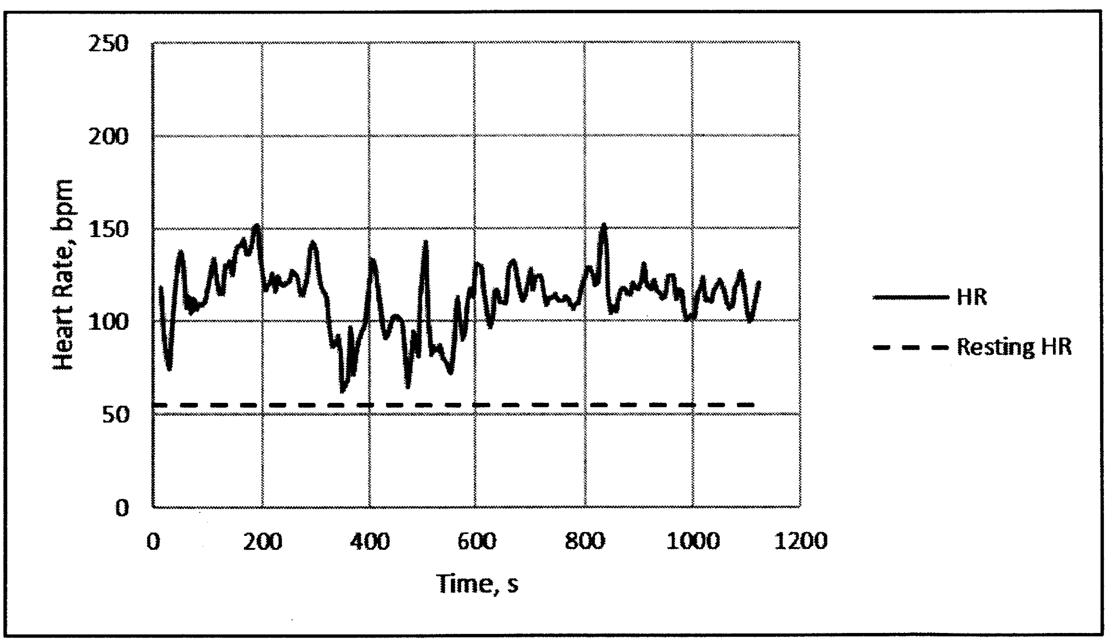

Figure A-2: Heart rate vs time for Traditional LFC over 2 roundtrip laps along 2 adjacent soccer fields; interference effects are less dramatic.

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