## AN ABSTRACT OF THE DISSERTATION OF

Iain Hunter for the degree of Doctor of Philosophy in Human Performance presented on July 12, 2001. Title: The Effect of a Near-Maximal Effort One-Hour Run on Preferred and Optimal Stride Rate and Vertical Stiffness.

Abstract approved: Redacted for Privacy

Gerald Smith

Experienced runners naturally optimize stride rate in a manner that minimizes oxygen uptake at given running speeds. However, as runners become fatigued, preferred stride rate often decreases. Whether such changes with fatigue occur in parallel with changes in optimal stride rate is unknown. This study's focus was on determining whether experienced runners self-optimize stride rate throughout a near-maximal one-hour run. A secondary focus was to determine if vertical stiffness is associated with decreases in stride rate.

Seventeen subjects completed a one-hour near-maximal effort run on a treadmill. After the first five minutes, preferred and optimal stride rates were measured. Ground reaction force data were used to determine preferred stride rate averaged over ten strides. Runners completed five two-minute segments of running at preferred stride rate, 4% and 8% above and below their preferred rate.

Oxygen uptake was measured during the second minute of each two-minute segment. Fitting a second-degree polynomial through oxygen uptake versus stride rate data provided a minimum value for oxygen uptake from which optimal stride rate was determined. Fifty minutes into the run, optimal stride rate was measured again.

Repeated measures ANOVA showed no difference between preferred and optimal stride rates at the beginning or at the end of the run, but a decrease in optimal stride rate was observed from beginning to end. About half of the subjects decreased preferred and optimal stride rate over the course of the hour run while the other half showed little or no change.

Vertical stiffness was measured based upon center of mass vertical displacement and active peak force. Decreases in preferred stride rate over the course of the hour run were expected to be associated with decreases of vertical stiffness. However, the changes in stride rate and vertical stiffness were small; no strong relationship was observed ($R^2=0.12$).

Experienced runners have demonstrated the capability to self-optimize stride rate at the beginning and near the end of a one hour run. This ability was observed for runners with substantial shifts of stride rate with fatigue as well as for runners with no change of stride rate with fatigue.

# The Effect of a Near-Maximal Effort One-Hour Run on Preferred and Optimal Stride Rate and Vertical Stiffness

By

Iain Hunter

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APPROVED:

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Major Professor, representing Human Performance

Redacted for Privacy

Chair of Department of Exercise and Sport Science

Redacted for Privacy

Dean of Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

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Iain Hunter, Author

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Dedicated to my dad
who always counseled me to “work hard”.

# THE EFFECT OF A NEAR-MAXIMAL EFFORT ONE-HOUR RUN ON PREFERRED AND OPTIMAL STRIDE RATE AND VERTICAL STIFFNESS

## CHAPTER 1
## INTRODUCTION

World records in distance running have been consistently improving in events from one mile to 6 days since the late 1800's (10). Even in this new millennium, world records are still falling at a nearly linear rate. Advancements in technique, training theory, physical capacity, nutrition, mental training, and other factors lead to athletes achieving times previously thought impossible. One aspect of running technique, stride rate, the number of strides occurring per second, has been studied in detail. Stride rate along with stride length are the two determining factors of speed. Coaches often tell athletes to adjust their stride length during competition and training. This may not be necessary and is perhaps harmful to performance. Cavanagh and Williams (4) observed that runners naturally select stride rates that minimize oxygen uptake. In addition, it is known that some runners naturally change preferred stride rate as they become fatigued. This paper will investigate these interrelationships of metabolic cost, fatigue and stride characteristics.

While at least one study demonstrated that experienced runners self-optimize stride rate in a rested state, no previous research has shown whether this self-optimization continues as runners become fatigued and perhaps alter their preferred stride rate from its initial state. The current study looked at experienced runners' abilities to self-optimize throughout a near-maximal effort one-hour run.

Fatigue induced changes in preferred stride rate have been observed in previous research (1, 3, 7, 8, 13). The reason for these changes is unclear. Perhaps changes in stride rate are due to physiological changes in the body. If the body is in a different state from the beginning to end of the run, optimal stride rate, the rate which minimizes oxygen uptake, could possibly change. If this is the case, the runner might be unknowingly modifying preferred stride rate to optimize running economy.

The physiological state of the body changes during a one-hour near-maximal effort run. Muscle temperature, hormone levels, energy sources, EMG activity, and pH are all altered from the beginning to end of fatiguing runs (2, 12, 9, 6). As a runner goes through the stance phase of a stride, eccentric and concentric muscle activity occurs. Energy is stored in muscles and tendons during the eccentric phase, then released during the concentric phase (5). A simple mass-spring model describes this motion quite well (Figure 1.1). This model describes the center of mass of the runner being attached to the ground by a spring during the stance phase of running. The main component of the spring is the leg (although other parts of the body are also incorporated). Since muscle state is altered with fatigue, elastic storage of the muscle may also change. Leg stiffness has been associated with decreased stride rate. The decreased stride rate commonly seen in fatigued runners may be associated with decreased leg stiffness.

Three research questions were investigated in this study. During an extended fatiguing run at constant speed, does optimal stride rate of runners decrease over the course of the run? Does optimal stride rate match with preferred stride rate even when a shift in optimal stride rate is observed? Finally, are stride rate changes associated with stiffness changes of the "leg spring".

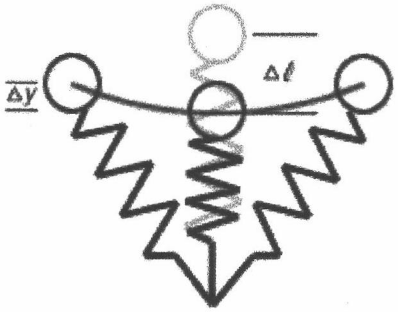

Figure 1.1
Mass-spring model of the body in running (Adapted from McMahon and Cheng, 11).

## *DEFINITIONS*

***Economy.*** Careful use of fuel (oxygen uptake is an indication of this).

***Economical running.*** Running with technique that minimizes oxygen uptake.

***Efficiency.*** The ratio of the useful energy delivered by a machine to the energy supplied to it

***Maximal oxygen uptake (max $\dot{V}O_2$).*** The maximum amount of oxygen the muscles can utilize from the blood for a given amount of time. This study will use units of milliliters per kilogram of body weight per minute (ml/kg/min).

***Optimal stride rate.*** The stride rate that minimizes oxygen use. Assuming there is only one optimal stride rate, as runners deviate from this rate, they will need to utilize more oxygen. This study will use units representing the number of strides per second (Hz).

***Preferred stride rate.*** The number of strides per second a runner naturally selects for a given speed.

***Segment.*** A two-:minute measurement where subjects were running at either preferred stride rate or an altered stride rate the entire time.

***Stage.*** A ten-minute measurement composed of five two-:minute segments where subjects ran at their preferred rate, then plus and minus four and eight percent of their preferred rate.

***Step.*** Half of a running stride. This is described as left to right or right to left.

***Stride.*** A complete cycle of running. This would be seen as the body being in a given position until the body returns to that position. The beginning of the stride can be defined at any point of a running cycle. For example, if the beginning of the stride is defined as right foot heel strike, the stride would end at the following right foot heel strike.

***Vertical ground reaction force (VGRF).*** The vertical force the ground exerts on the body.

***Vertical Stiffness.*** Peak vertical ground reaction force divided by the displacement of the center of mass during the stance phase of running

## *REFERENCES*

1. Bates, B. T. and L. R. Osternig. Fatigue effects in running. *Journal of Motor Behavior*, 9:203-207, 1977.

2. Binder-Macleod, S. A., S. Lee, A. D. Fritz, and L. J. Kucharski. A new look at force-frequency relationship of human's skeletal muscle: Effects of fatigue. *Journal of Neurophysiology*, 79:1858-1868, 1998.

3. Candau, R. et al. Energy cost and running mechanics during a treadmill run to voluntary exhaustion in humans. *European Journal of Applied Physiology*. 77:479-485, 1998.

4. Cavanagh, P. R. and K. R. Williams. The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise*. 14:30-35, 1982.

5. Dalleau G., A. Belli, M. Bourdin, J. R. Lacour. The spring-mass model and the energy cost of treadmill running. *European Journal of Applied Physiology and Occupational Physiology*. 77:257-263, 1998.

6. De Haan, A., D. A. Jones, and A. J. Sargeant. Changes in velocity of shortening, power output and relaxation rate during fatigue of rat medial gastrocnemius muscle. *European Journal of Physiology*. 413:422-428, 1989.

7. Dutto, D. *Leg spring model related to muscle activation, force, and kinematical patterns during endurance running to voluntary exhaustion*. Unpublished doctoral dissertation, Oregon State University, Corvallis, OR. 2000.

8. Elliott, B and T. Ackland. Biomechanical effects of fatigue on 10,000 meter running technique. *Research Quarterly for Exercise and Sport*. 52:160-166, 1981.

9. Farrell, P. A., J. H. Wilmore, E. F. Coyle, J. E. Billing, and D. L. Costill. Plasma lactate accumulation and distance running performance. *Medicine and Science in Sports and Exercise*, 11:338-344, 1979.

10. Lloyd, B. B. The energetics of running: an analysis of world records. *Advanced Science*, 22:515-530, 1966.

11. McMahon T. A. and G. C. Cheng. The mechanics of running: how does stiffness couple with speed? *Journal of Biomechanics.* 23 Suppl 1:65-78, 1990.

12. Pinniger, G. J., J. R. Steele, and H. Groeller. Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Medicine and Science in Sports and Exercise.* 32:647-653, 2000.

13. Williams, K. R, R. Snow, and C. Agruss. Changes in distance running kinematics with fatigue. *Medicine and Science in Sports and Exercise.* 20:S49, 1988.

# CHAPTER 2

# THE EFFECT OF A NEAR-MAXIMAL EFFORT ONE-HOUR RUN ON PREFERRED AND OPTIMAL STRIDE RATE AND VERTICAL STIFFNESS

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## *ABSTRACT*

***Purpose.*** This study focused on determining whether experienced runners were able to self-optimize stride rate initially and at the end of a near-maximal one-hour run.

***Methods.*** Seventeen subjects completed a one-hour near-maximal effort run on a treadmill at a fixed speed slightly slower than each individual's 10 km race pace.

Preferred and optimal stride rates were measured near the beginning and end of the hour run.

***Results.*** A decrease in optimal stride rate was observed between initial and final readings. Two-way ANOVA showed no difference between preferred and optimal stride rates at the beginning or at the end of the run. Half of the subjects decreased preferred and optimal stride rate over the course of the hour run while the other half showed little or no change. No significant association was found between changes in vertical stiffness and changes in stride rate

***Conclusion.*** Experienced runners demonstrate the capability to self-optimize stride rate at the beginning of a run and when very fatigued near the end of an hour run. This consistent ability was observed for runners with substantial shifts of stride rate with fatigue as well as for runners with no change of stride rate with fatigue. The ability to self-optimize despite changing optimal rates may help runners maintain given speeds for longer times than would be possible if constant

stride rate were maintained for the full time. Further research needs to be performed to determine why stride rate changes in some runners.

## *INTRODUCTION*

Using economical technique helps runners maintain higher speeds and continue running for a longer time than if they used a less economical technique. Determining which aspects of technique to modify and which to leave alone can be a difficult decision for coaches and athletes. Cavanagh and Williams (6) found runners naturally self-optimize stride rate and length to minimize oxygen uptake. Their study used athletes who were non-fatigued. An interesting consideration is whether runners are still capable of this self-optimization even when they become fatigued. Previous studies have shown that runners often alter their preferred stride rate when they become fatigued even when speed is held constant (1, 5, 11, 12, 22). The changes in preferred stride rate were most commonly decreases, however, there were some cases where no change or even small increases were observed. Past studies generally discuss stride rate rather than stride length. Speed equals the product of stride rate and stride length. This study will also discuss stride rate, but it should be realized that the results could easily be translated into stride length by dividing speed by stride rate.

It is unclear why preferred stride rate changes in some runners and not in others. However, it does make sense that stride rate could change. Many physiological changes occur in muscle as runners become fatigued. During extended periods of running, hydrogen ions ($H^+$) are released from lactic acid and inorganic phosphate ($P_i$) is released in the degradation of ATP. Phosphofructokinase is inhibited by $H^+$, which leads to decreases in glycolytic capacity and disassociation of calcium ions from troponin, interfering with muscle contraction. If the run is sufficiently above lactate threshold, increases in $P_i$ will bind to calcium in the sarcoplasmic reticulum, decreasing force at the actin-myosin crossbridges. Finally, the decreased pH may result in pain (3). Fatigue is a very complex issue, but for a one-hour near maximal effort run, as was used in this study, the increases in $H^+$ and $P_i$ are likely the main factors leading to exhaustion.

The changes occurring on the cellular level help explain alterations in muscle capacities. Running involves concentric, eccentric, and isometric muscle activity. When muscles become fatigued, a reduction in isometric peak force occurs (10), hamstring peak torque creation is decreased (18), and maximum shortening velocity is reduced (10). While the muscles are probably not required to reach peak isometric force or maximum shortening velocity in running, these muscular limitations are evidence of physical changes which may lead to altered technique.

Motor unit firing frequency is linearly related to motor unit force. This force-frequency relationship suggests that muscle can create greater force with increased activation frequency. As muscles become fatigued, there is a change in the force-frequency relationship. In a fatigued state, activation frequency must be increased to maintain force production (2).

Pinniger found that EMG duration increases as runners become fatigued, starting earlier and finishing later around the stance phase (18). Slight technique changes were associated with the increases in EMG duration in Pinniger's study, including a decrease in stride rate. Pinniger also found significant decreases in hamstring peak torque creation in fatigued muscle (18). While running does not require a person to create peak torques, the muscle is obviously in a different state if its performance level is altered.

Tendons and bones may suffer microdamage during extended repetitious exercise. As tissues become damaged due to repetitious exercise, it seems likely that locomotion may undergo altered technique to minimize further damage, which may affect movement economy. Changes in stride rates may take place to decrease impact frequency or peak force.

The fatigue induced changes described above may lead to a decreased vertical stiffness which when modeled using a simple mass-spring has been calculated using peak vertical ground reaction force divided by the displacement of the center of mass during the stance phase of running. With speed of muscle contraction diminished, it follows that the leg may not be able to act as stiffly as in a non-fatigued state. So, as runners become fatigued, vertical stiffness may be decreased.

Increases in vertical stiffness have been associated with increased stride rate. If the physiological changes in muscle lead to decreases in vertical stiffness, then the observed decreases in stride rate could be partly explained.

There are times when running economy is not the main issue. For example, near the beginning or end of a distance race or in short races, speed is the primary concern. In these situations, athletes may sacrifice running economy for speed.

The results of this study apply only to the issue of running economy rather than optimizing technique for every running situation.

Many physiological changes occur during extended running. When preferred stride rate changes during a run, the runner may be adjusting technique to accommodate to these physiological changes. This study investigated whether runners self-optimize stride rate during the initial and final stages of a near-maximal effort one-hour run and tested the hypothesis that decreased stride rate is associated with decreased vertical stiffness.

## *METHODS*

***Subjects.*** Seventeen subjects (five female, 12 male) from the university population between ages 20 and 44 participated in the study. All were required to have been running at least 20 miles per week for the past four weeks prior to data collection. Subjects were free of any heart disease risk factors and injury that could affect their performance. Gender, age, height, weight, and max $\dot{V}O_2$ can all be found in Table 2.1.

***Questionnaire.*** A health risk questionnaire was used in a screening process to find any runners who may have increased heart attack risk during a maximum oxygen uptake (max $\dot{V}O_2$) test. This questionnaire is included in Appendix A.

Risks, benefits, and procedures were explained to each subject prior to participation. An informed consent document was signed by each subject before he/she was allowed to begin. The Oregon State University Institutional Review

| Subject | Gender | Age (yr) | Height (cm) | Weight (kg) | Max $\dot{V}O_2$ |
|---|---|---|---|---|---|
| 1 | M | 29 | 175 | 70 | 61.7 |
| 2 | M | 31 | 193 | 87 | 62.0 |
| 3 | M | 29 | 185 | 88 | 60.7 |
| 4 | F | 20 | 165 | 50 | 51.6 |
| 5 | F | 33 | 173 | 63 | 52.1 |
| 6 | M | 44 | 193 | 79 | 57.4 |
| 7 | M | 30 | 175 | 70 | 65.3 |
| 8 | M | 20 | 180 | 68 | 59.1 |
| 9 | F | 33 | 163 | 59 | 54.6 |
| 10 | M | 23 | 183 | 84 | 45.6 |
| 11 | M | 23 | 163 | 64 | 64.7 |
| 12 | F | 20 | 165 | 66 | 49.4 |
| 13 | M | 23 | 173 | 69 | 67.1 |
| 14 | F | 21 | 163 | 60 | 59.1 |
| 15 | M | 42 | 173 | 75 | 61.7 |
| 16 | M | 21 | 185 | 73 | 68.3 |
| 17 | M | 29 | 177 | 70.9 | 66.4 |
| Mean |  | 27.7 | 176 | 70.3 | 59.2 |
| Standard Deviation |  | 7.4 | 10 | 10.2 | 6.6 |

Table 2.1
Subject Characteristics

Consent Form, and Institutional Review Board approval are included in Appendix B.

***Preliminary run.*** Three runs were required of each subject. The first of these was described to the subjects as a preliminary run. The goal of this run was to determine a pace the subjects could maintain for one hour, but approaching exhaustion at the one hour mark. The run began at a pace based upon what each subject estimated he/she could sustain. If necessary, pacing charts were used to help subjects predict an appropriate pace based upon current racing performances (Table 2.2). Initial predictions of appropriate pace were not always acceptable. During the first half of each preliminary run, treadmill speed was often altered until the subject and researchers felt an optimal pace for the study had been estimated.

| **10 K (min)** | **60 min run (mi)** | **per mile @60 min run pace** | **m/s @60 min run pace** | **m/min @60 min run pace** |
|---|---|---|---|---|
| 28 | 11.0 | 5.45 | 4.91 | 294.8 |
| 29 | 10.9 | 5.53 | 4.85 | 290.8 |
| 30 | 10.7 | 5.61 | 4.78 | 286.8 |
| 31 | 10.6 | 5.69 | 4.71 | 282.7 |
| 32 | 10.4 | 5.77 | 4.65 | 278.7 |
| 33 | 10.3 | 5.85 | 4.58 | 274.7 |
| 34 | 10.1 | 5.94 | 4.51 | 270.7 |
| 35 | 10.0 | 6.03 | 4.44 | 266.7 |
| 36 | 9.8 | 6.12 | 4.38 | 262.6 |
| 37 | 9.7 | 6.22 | 4.31 | 258.6 |
| 38 | 9.5 | 6.32 | 4.24 | 254.6 |
| 39 | 9.4 | 6.42 | 4.18 | 250.6 |
| 40 | 9.2 | 6.52 | 4.11 | 246.6 |
| 41 | 9.1 | 6.63 | 4.04 | 242.5 |
| 42 | 8.9 | 6.74 | 3.98 | 238.5 |
| 43 | 8.8 | 6.86 | 3.91 | 234.5 |
| 44 | 8.6 | 6.98 | 3.84 | 230.5 |
| 45 | 8.5 | 7.10 | 3.77 | 226.5 |

Table 2.2
Pacing Chart

***Data collection run.*** At least one week was given between the preliminary run and the data collection run. On the day of the data collection run, the runners were allowed to warm up for five minutes at any pace they desired. After the warm-up, the entire run was completed at the predetermined pace. The run began with a five-minute stage of unmonitored running. This was sufficient time to reach a stable $\dot{V}O_2$ measurement, which typically happens within one to four minutes depending upon the workload and level of training, and also helped in technique accommodation to the treadmill (4, 7, 19). Following the first five minutes, runners completed a stage including two-minute segments of running at their preferred stride rate, four and eight percent above and below their preferred rate. The latter four stride rates were completed in random order. From this 15 minute point, runners continued without having stride rate manipulated for another 35 minutes, bringing them to 50 minutes into the run. After 50 minutes of running, the final 10 minutes were similar to the manipulated stride rate stage that took place near the beginning of the run, but a new randomization of altered stride rates was used. Figure 2.1 shows an example of how optimal stride rate was calculated in a typical subject.

The process of calculating optimal stride rate involves measuring oxygen uptake through a range of various stride rates. Cavanagh and Williams (6) measured oxygen uptake at seven different stride rates through a range of approximately 12% of preferred stride rate, using a metronome to help subjects match the rates. Plus and minus four and eight percent have been chosen here due

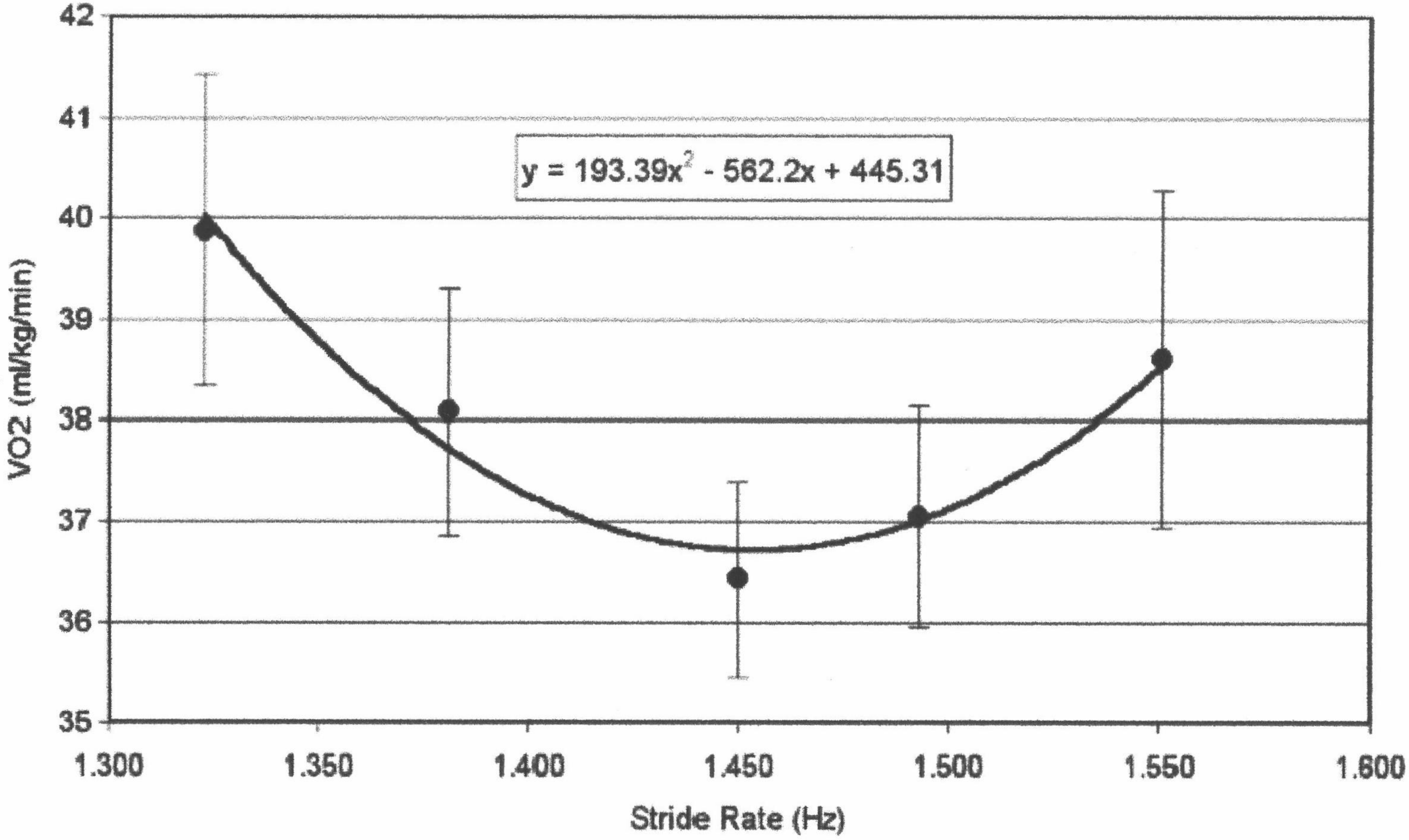

Figure 2.1
Calculation of optimal stride rate. Middle point represents oxygen uptake at preferred stride rate. Minimum value of curve represents oxygen uptake at optimal stride rate.

to the higher speeds of running expected (as fast as 5:50 min/mi), which make it difficult to adjust dramatically away from preferred stride rate. Runners matched the cadence of a computer-based metronome to keep them on the determined stride rate. The metronome was not used during the preferred rate segment to allow the runners to naturally select their stride rate.

During the first minute of the preferred segment of each stage, vertical ground reaction forces from instrumentation built into the treadmill were measured for nine seconds and plotted on a computer monitor. This was sufficient time to display force data for at least 10 strides. A program was written using Visual Basic to provide time information by clicking on ending and beginning of the ten strides enabling a preferred stride rate estimation. The plus and minus four and eight percent stride rates were based upon this estimation. During the second minute of the preferred stride rate and during all four stride rate manipulations 30 seconds of force data were collected. Average stride rate for each condition was taken after the run using the 30 second force data collections. All force measurements were taken at 500 Hz.

In order to allow accommodation to new stride rates and a new steady state oxygen uptake, measurements of oxygen uptake took place during the second minute of the preferred and altered stride rate segments. Although one minute is not much time to reach steady state exercise from rest, the changes in oxygen uptake with new stride rates were so small that one minute was sufficient.

Preferred stride rate was also measured using ten-stride averages from ground reaction force data every five minutes during the run. This provided a description of the time course of stride rate change throughout the run.

Treadmill speed was checked periodically with a handheld digital tachometer (Model 21C13, Kernco Instruments Co.) to ensure constant speed throughout the run.

***Instrumented treadmill.*** Vertical force was measured using an instrumented treadmill (Figure 2.2). The treadmill bed was mounted on a concrete slab completely separated from the motor except for the drive belt. Six force transducers exist under the treadmill bed to measure vertical force. A Computer Boards DAS/1200 Jr converted the voltage difference across each transducer into a digital value which was then converted to force units of Newtons. Over time, the voltages from the six transducers drifted downwards. This drift was adjusted for before any calculations were performed. Throughout the flight phase of a running stride, the runners were not placing any force on the treadmill. Since the true force here was zero, the rest of the force readings for the current step were adjusted accordingly. Summing the values from all six transducers provided the vertical force of the runner.

Some low amplitude noise existed in measurements from this treadmill as can be seen in the force tracing of Figure 2.3. Testing of the treadmill at speeds likely to be used in the present study showed the frequency of the noise to be

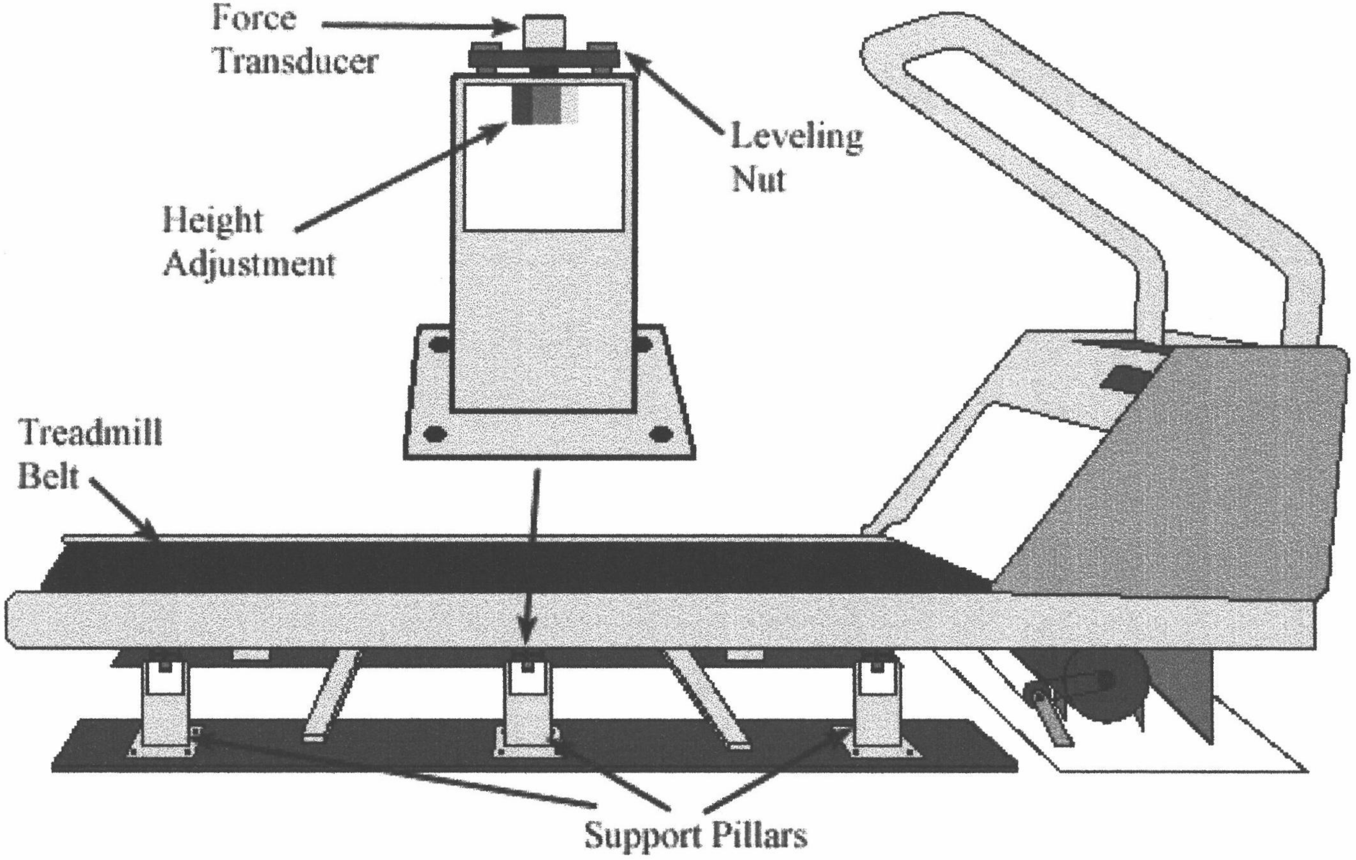

Figure 2.2
Diagram of instrumented treadmill.

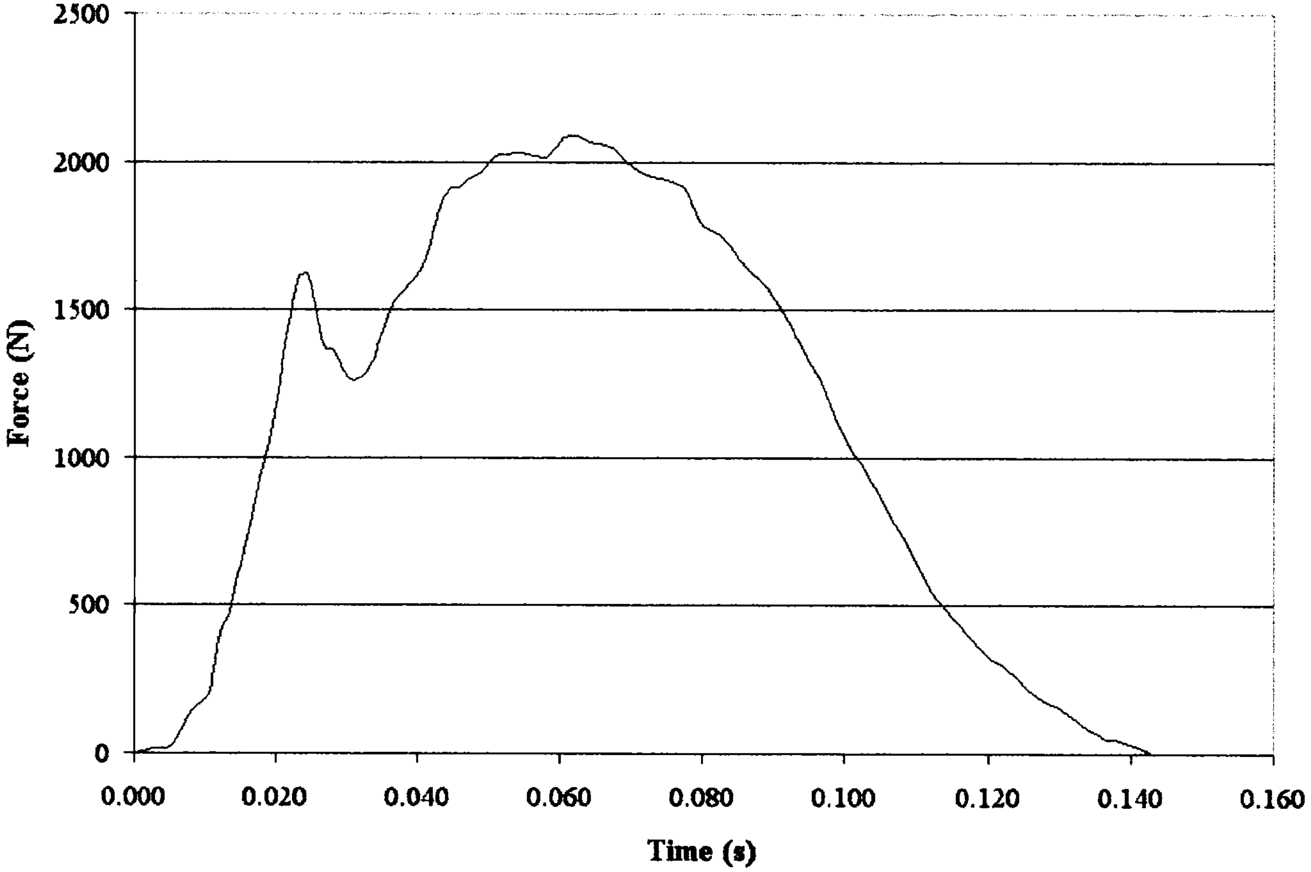

Figure 2.3
Example of signal noise in typical force tracing from instrumented treadmill.

approximately 12 Hz, but varied slightly with the speed of the treadmill. The 12 Hz frequency was determined using a Fourier frequency analysis. Noise of this frequency cannot be reasonably filtered out because it overlaps with the true signal. The force signal characteristics used for calculating vertical stiffness and measuring stride rate were expected to be unaffected by the low amplitude noise present in the instrumented treadmill output. This was tested by artificially introducing similar noise to a clean ground reaction force-time data set. Vertical stiffness was affected minimally by such noise contamination.

Each transducer of the treadmill was independently calibrated off of the device. Loads to about 300 N were systematically applied to a transducer and its voltage output measured through the computer's analog-digital conversion system used for the experiment (Appendix F). Reassembled, the complete treadmill instrumentation determined subject body weight with error of less than 1% compared with a Kistler force plate measurement.

***Vertical stiffness calculation.*** Vertical stiffness was calculated during the time intervals where optimal stride rate was determined. A total of 10 stiffness values (five left and five right) were averaged for each stride rate with only the average values used in the final analysis.

Vertical stiffness was measured by calculating the slope on a force versus center of mass vertical displacement graph. The instrumented treadmill was used to monitor vertical force. Center of mass displacement was calculated by taking a double integral of the force data. The following is a description of how this is done.

Vertical stiffness was calculated by dividing peak force by center of mass vertical displacement at the time of peak force. The treadmill provides force values, but center of mass vertical displacement needs to be calculated. After subtracting body weight, dividing force by mass provides acceleration values of the center of mass. After determining two initial conditions, a double integration can be performed on the acceleration data to provide instantaneous position.

Notation used in following derivation:

$f$=force
m=mass
T=time from heel contact of one foot to heel contact of the other foot
v=instantaneous velocity
$v_0$=initial velocity
$y$=instantaneous vertical position
$y_0$=initial position
$\Delta y$=vertical displacement of center of mass

First, instantaneous velocity depends on initial velocity and acceleration:

$$v(t) = v_0 + \int_0^t \frac{f(t)}{m} dt$$

Instantaneous vertical position depends on initial position and vertical velocity:

$$y(t) = y_0 + \int_0^t v(t)dt = y_0 + \int_0^t \left[ v_0 + \int_0^t \frac{f(t)}{m} dt \right] dt = y_0 + v_0 t + \int_0^t \int_0^t \frac{f(t)}{m} dtdt$$

Take $y_0 = 0$, so: $y(t) = v_0 t + \int_0^t \int_0^t \frac{f(t)}{m} dtdt$.

But over a cycle of time T, $\Delta y = 0$: $y(0) = y(T)$, it is assumed that $y_0 = 0$, $y(T) = 0$.

$$v_0 T + \int_0^T \int_0^T \frac{f(t)}{m} dtdt = 0$$

Therefore, initial velocity, $v_0 = -\dfrac{\int_0^T \int_0^T \frac{f(t)}{m} dtdt}{T}$.

Finally: $y(t) = v_0 t + \int_0^t \int_0^t \frac{f(t)}{m} dtdt = \left[ -\dfrac{\int_0^T \int_0^T \frac{f(t)}{m} dtdt}{T} \right] t + \int_0^t \int_0^t \frac{f(t)}{m} dtdt$.

With vertical position of the center of mass determined at all times during stance, maximum displacement can be calculated. Dividing the maximum force at the time of maximum vertical displacement by the maximum vertical displacement gives the vertical stiffness. This is the positive value of the average slope of the line shown in Figure 2.4.

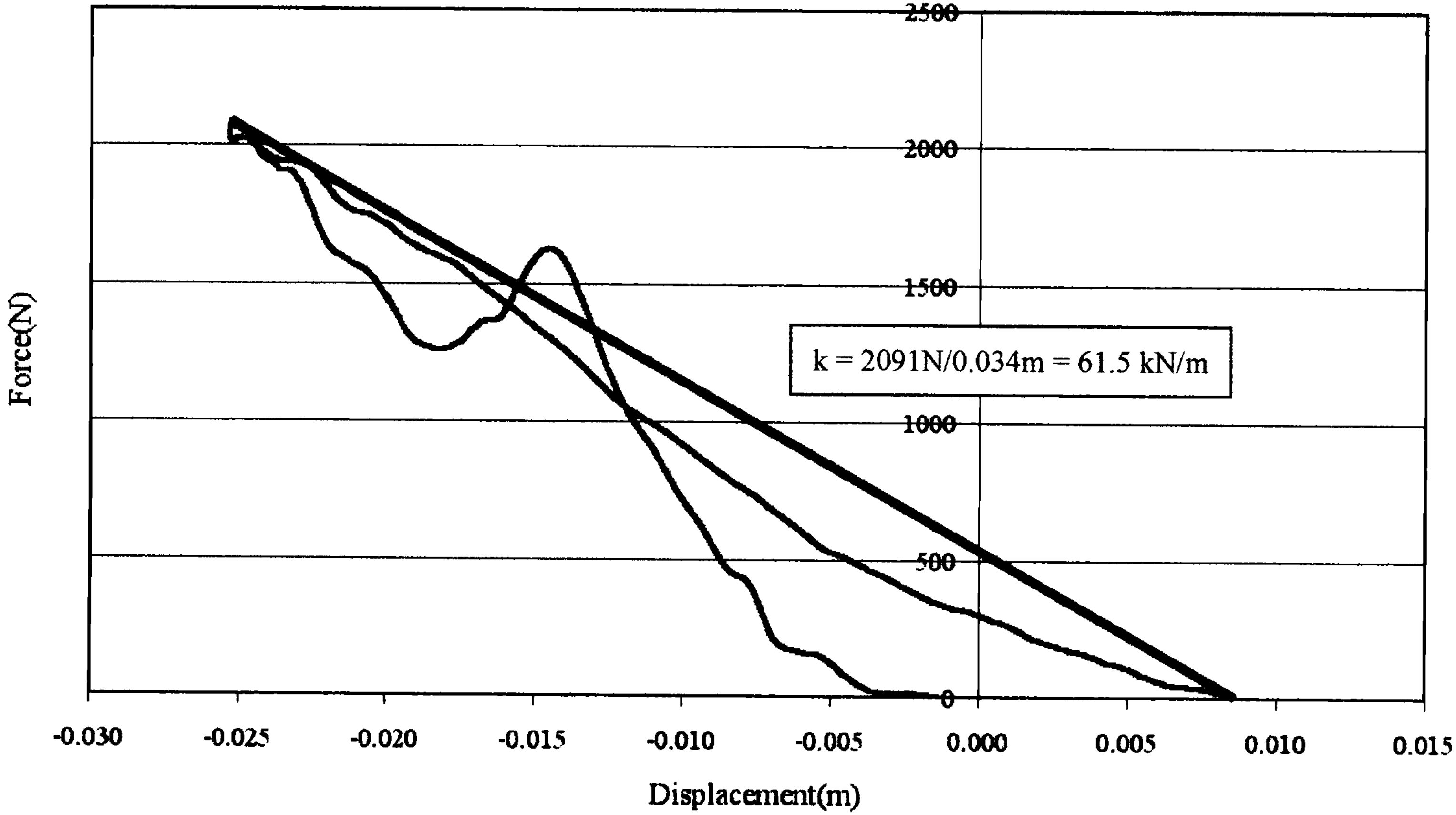

Figure 2.4
Calculation of vertical stiffness.

***Maximum oxygen uptake test.*** A maximum oxygen uptake (max $\dot{V}O_2$) test was administered to each subject. The test began with four minutes of running at six miles per hour (mph). At the beginning of minute five, speed was increased by 0.5 mph. Speed increases of 0.5 mph continued every following minute until nine mph was reached. At this point, speed was held at a constant nine mph, but grade was increased by one percent each minute. These grade increases continued until subjects indicated they could not continue any further. Every few minutes and every minute near the end of the run, subjects were asked how they were feeling, if they could complete the stage they were running, and if they felt capable of beginning another stage. They responded with a "thumbs up" or "thumbs down". If they were not able to finish the stage, the test was discontinued. However, subjects were encouraged to run as many 20-second segments as possible since oxygen uptake readings were given by the metabolic cart every 20 seconds.

Care was taken to make ensure subjects reached $\dot{V}O_2$ max rather than just a $\dot{V}O_2$ peak. This was done by looking for a plateau of $\dot{V}O_2$ readings, a respiratory quotient well above 1.00, and a heart rate near age-predicted max.

The oxygen uptake during the preferred stride rate segment at the beginning and end of the run were divided by the max $\dot{V}O_2$ to give us the percent of their maximal aerobic capacity each subject was running. This provided an indication of relative intensity of the hour run and indirectly a sense of "fatigue" to be expected.

A metabolic cart (Model 2900, SensorMedics) was used to measure oxygen uptake. Calibration took place before each use. Oxygen uptake was sampled every 20 seconds. Since collection during each segment of the run covered a full minute, the three values provided were averaged to give the oxygen uptake for each measured stride rate.

***Analysis.*** Following data collection, initial and final preferred and altered stride rates were measured using the 30 second samples of force data. A program created with Visual Basic, displayed graphs of small sections of the dataset at a time. Individual strides were then picked out by clicking on the beginning and end of the each stride. This continued stride by stride throughout the sample, providing an average rate for each stride segment. Rather than assuming the metronome's rate was matched by the subjects, these measured stride rates were used in the analysis.

Oxygen uptake was measured during the second minute of each preferred and altered stride rate. A second-degree polynomial was created with the five oxygen uptake samples as a function of stride rate. The minimum value of this function represented optimal stride rate.

***Statistical analysis.*** A two-way analysis of variance with an alpha level of 0.05 was used to determine differences between preferred and optimal stride rates across the initial and final parts of the run. Tukey-Kramer post-hoc multiple comparison tests were used to distinguish which groups were significantly different from one another. While our groups were not independent of each other, the post-hoc tests along with confidence intervals made it clear where the differences occurred.

***Assumptions.*** It was assumed that the range of stride rates used in calculating optimal stride rate would include a minimum oxygen uptake value. This assumption had been previously tested by Cavanagh and Williams (6) who found optimal and preferred stride rate to be almost equal in a non-fatigued state.

Measurement of preferred stride rate was based on a 30 second sampling. Preferred stride rate is slightly variable from step to step, but 30 seconds was a long enough period to obtain a stable measurement. In a similar study, Cavanagh and Williams used a 20 second measurement (6).

Males and females were accepted into the study without any restriction to distribution. Other than running speed, no differences in measured variables were expected to be found.

***Limitations.*** Oxygen uptake measurements were only taken for two-minute intervals in this study. Technique was being altered at the beginning of each two-minute interval. Some amount of time was required to arrive at a steady-state of oxygen uptake before valid readings could be made. This allowed about one minute of useable $\dot{V}O_2$ measurement. While this was probably sufficient to get a good estimate, more time would have been desirable to decrease variability. However, with the design described in the methods and procedures section, each optimal stride rate measurement already took ten minutes. Manipulating technique for much longer than this could have produced some fatigue induced changes in the body that would affect results. Another drawback to having limited time to measure optimal stride rate, was that only five different stride rates were used in the optimal stride rate calculation. More stride rate manipulations would have given a more accurate value for optimal stride rate. Thus, due to the overall experimental design, the amount of time that could be taken to measure optimal stride rate was limited.

The speeds of the data collection runs needed to be very close to each subject's maximal effort for a one-hour run. This was estimated from pacing charts and results from a preliminary run. However, day-to-day changes in physical capacity and motivation during the preliminary run may have limited how close to exhaustion each subject became.

## ***RESULTS***

***ANOVA.*** Repeated measures ANOVA showed strong evidence of a difference between groups ($p<0.0001$, power=0.99). Tukey-Kramer multiple comparison tests along with confidence intervals showed decreases in preferred and optimal stride rates from beginning to end of the run. No significant difference was observed between preferred and optimal stride rates during either initial or final portions of the run.

***Preferred stride rate changes.*** An average decrease of 1.7% was found in preferred stride rate from initial to final measurements. Between subjects much variability was observed (SD=2.4% of the mean). Within subjects, the average standard deviation for each stride rate measurement was 0.9% of the mean. Figures 2.5, 2.6, and 2.7 show individual stride rate profiles throughout the run demonstrating how differently each runner adjusted preferred stride rate.

***Optimal stride rate changes.*** Optimal stride decreased, on average, by 1.8%. Significant differences between initial and final optimal stride rate measurements were observed. About half of the subjects showed minimal changes in optimal stride rate while the rest showed decreases. While statistically significant changes were found in optimal stride rate, a more informative description of what occurred would be to describe changes on an individual basis since some subjects had no change in optimal stride rate.

***Similarity of preferred and optimal stride rates.*** Average preferred and optimal stride rates were very similar during initial and the final measurements (Table 2.3 and Figures 2.8, 2.9, and 2.10). The initial stage showed an average positive difference between preferred and optimal of 0.005 Hz. The final stage showed an average positive difference of 0.006 Hz. Standard deviations and confidence intervals for preferred and optimal stride rates were almost identical.

Although some subjects deviated slightly from optimal stride rate, the largest increase in oxygen uptake due to this deviation was 0.038 ml/kg/min (average increase=0.005 ml/kg/min). A summary of metabolic changes is found in Table 2.4.

***Vertical stiffness changes.*** Mean initial and final vertical stiffness values were 26.6 kN/m and 26.4 kN/m respectively. Within subject standard deviation

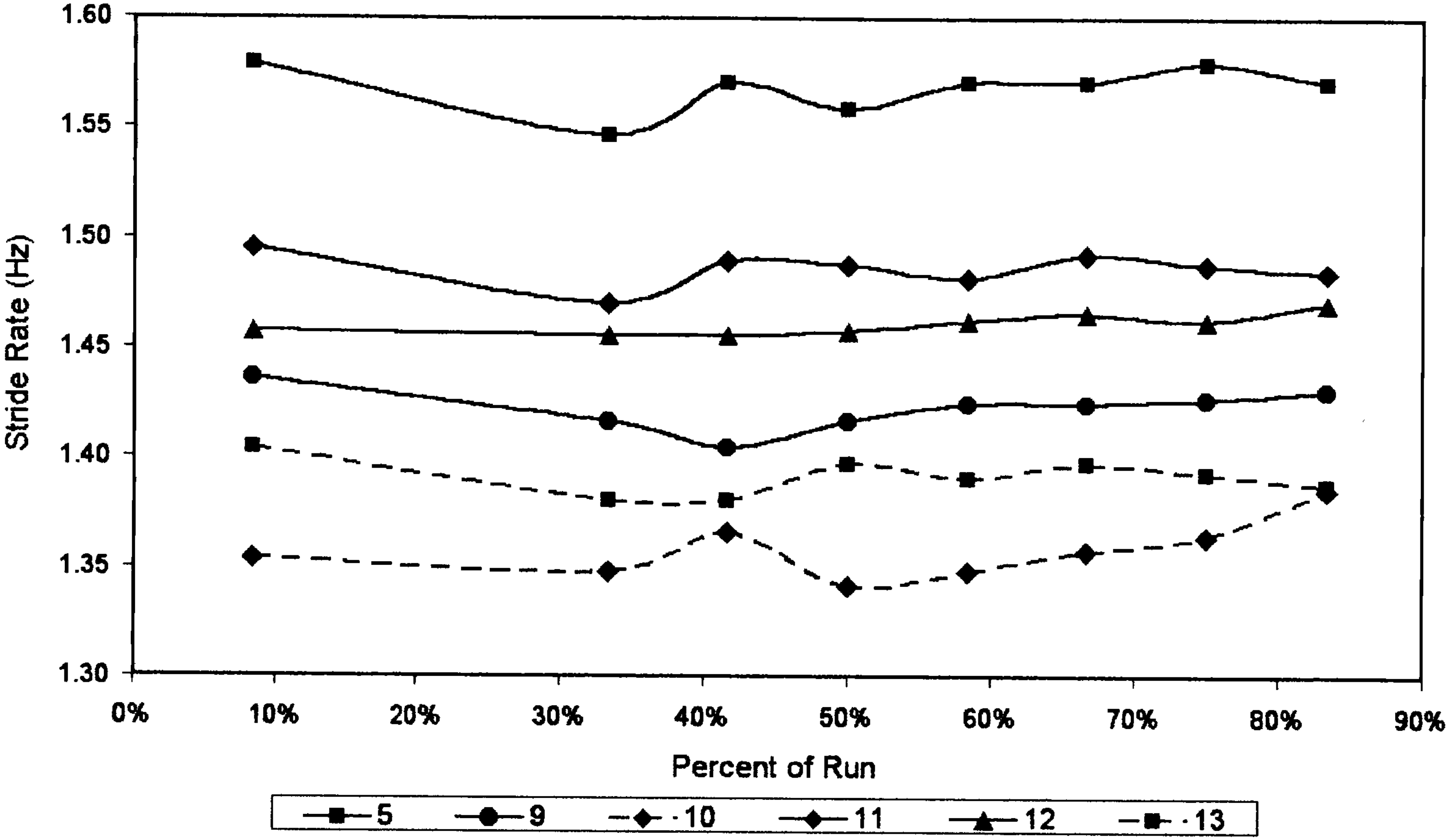

Figure 2.5
Subjects who showed little change in preferred stride rate.

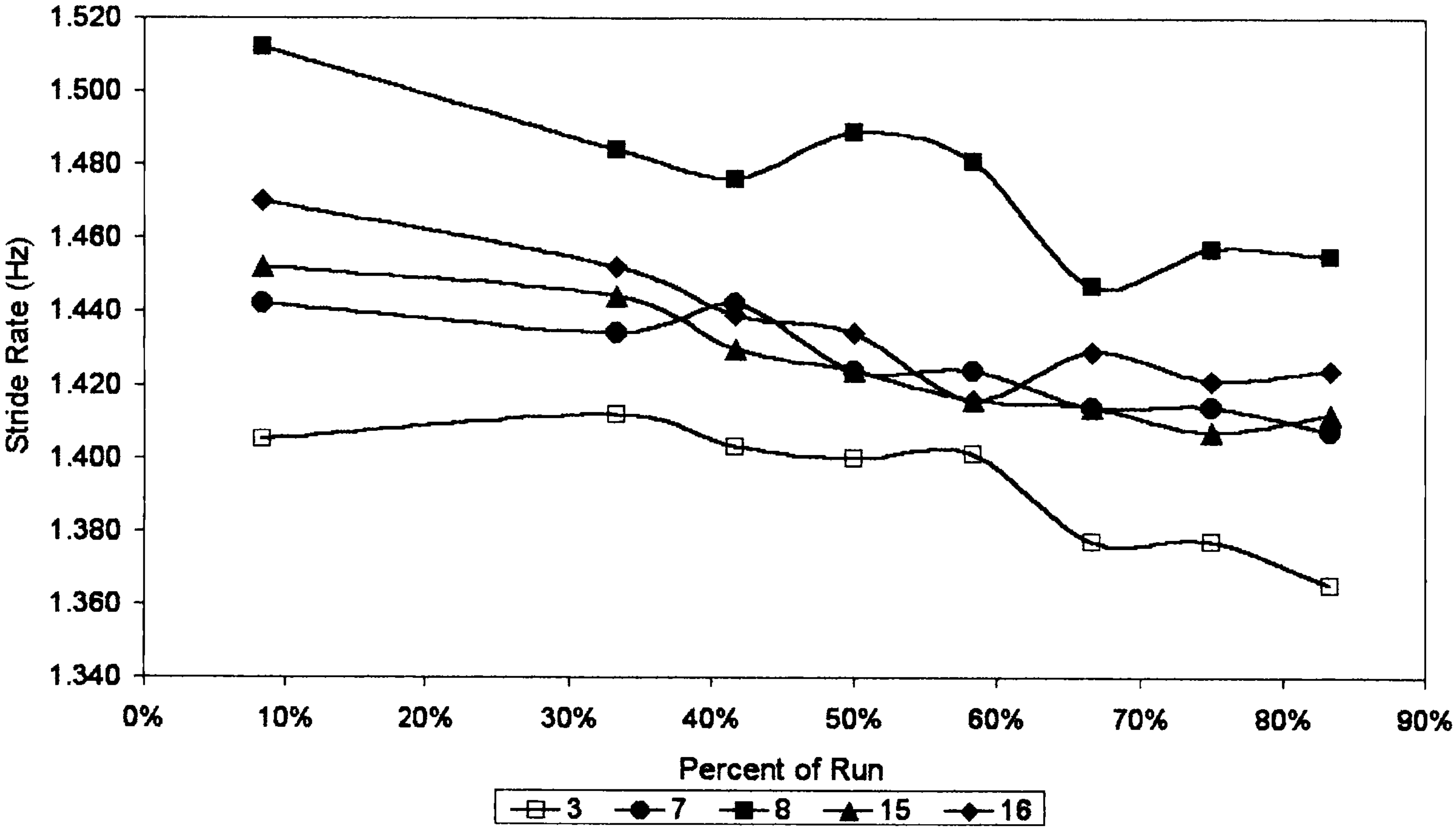

Figure 2.6
Subjects showing systematic decreases in preferred stride rate.

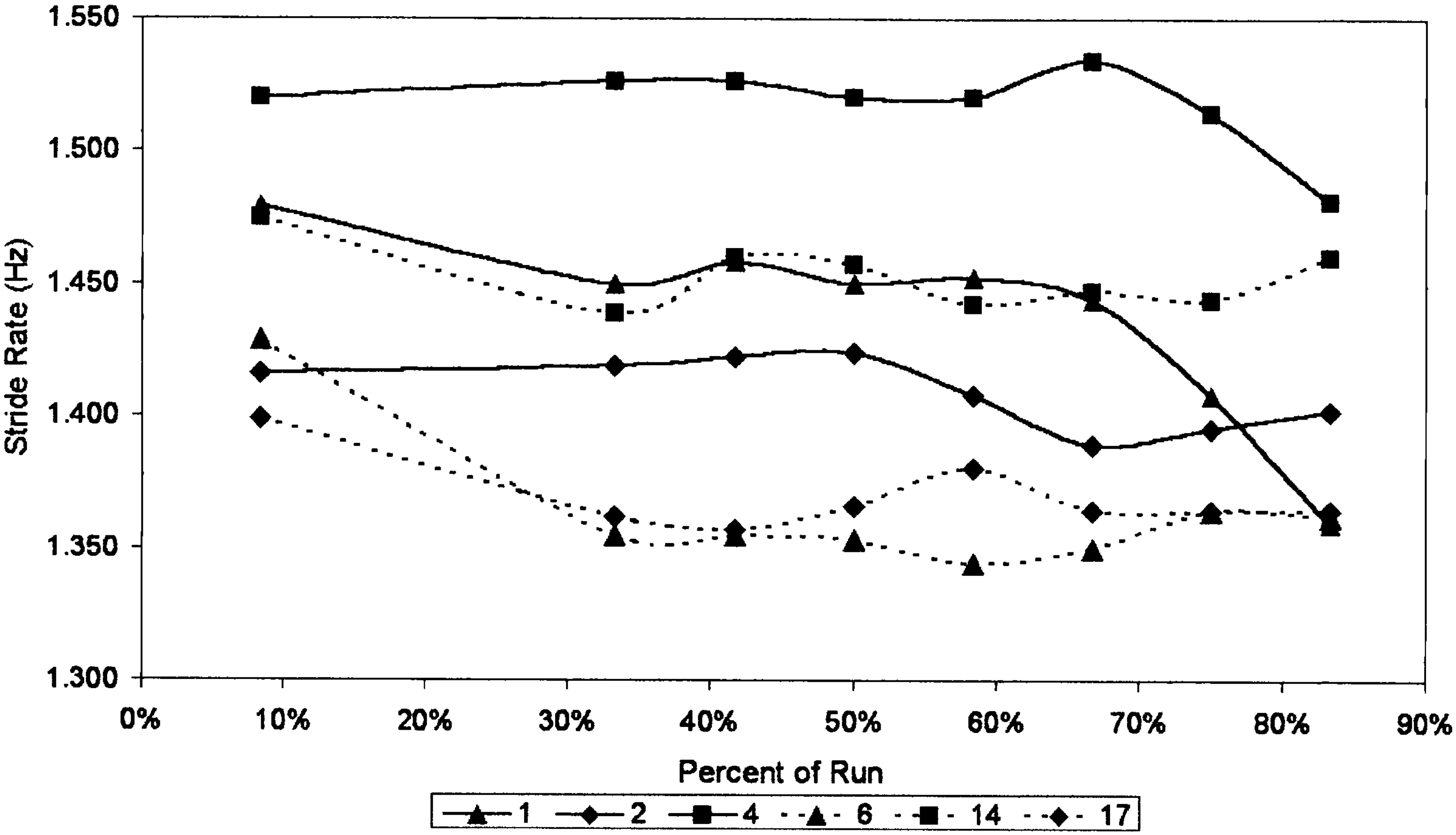

Figure 2.7
Subjects showing non-systematic decreases in stride rate.

| | Pref SR (Hz) | | | Optimal SR (Hz) | | |
|---|---|---|---|---|---|---|
| **Subject** | **Initial** | **Final** | **Change** | **Initial** | **Final** | **Change** |
| 1 | 1.470 | 1.349 | -0.121 | 1.478 | 1.360 | -0.118 |
| 2 | 1.389 | 1.398 | 0.009 | 1.400 | 1.388 | -0.012 |
| 3 | 1.405 | 1.365 | -0.040 | 1.403 | 1.361 | -0.042 |
| 4 | 1.513 | 1.501 | -0.012 | 1.501 | 1.496 | -0.005 |
| 5 | 1.573 | 1.570 | -0.003 | 1.569 | 1.563 | -0.005 |
| 6 | 1.410 | 1.362 | -0.048 | 1.422 | 1.377 | -0.045 |
| 7 | 1.412 | 1.425 | 0.013 | 1.405 | 1.424 | 0.018 |
| 8 | 1.504 | 1.483 | -0.021 | 1.510 | 1.476 | -0.034 |
| 9 | 1.450 | 1.450 | 0.000 | 1.454 | 1.457 | 0.004 |
| 10 | 1.350 | 1.356 | 0.006 | 1.350 | 1.352 | 0.002 |
| 11 | 1.501 | 1.480 | -0.021 | 1.511 | 1.484 | -0.027 |
| 12 | 1.465 | 1.474 | 0.009 | 1.467 | 1.487 | 0.020 |
| 13 | 1.405 | 1.389 | 0.016 | 1.405 | 1.390 | -0.015 |
| 14 | 1.480 | 1.474 | -0.006 | 1.485 | 1.470 | -0.015 |
| 15 | 1.478 | 1.412 | -0.066 | 1.479 | 1.416 | -0.063 |
| 16 | 1.475 | 1.407 | -0.068 | 1.471 | 1.409 | -0.062 |
| 17 | 1.346 | 1.305 | -0.041 | 1.350 | 1.304 | -0.046 |
| **Average** | 1.449 | 1.424 | -0.025 | 1.451 | 1.424 | -0.026 |
| **Std Dev** | 0.061 | 0.068 | 0.036 | 0.060 | 0.066 | 0.035 |
| **95% CI** | 1.419 to1.479 | 1.391 to1.457 | -0.042 to -0.008 | 1.422 to 1.480 | 1.391 to 1.457 | -0.043 to 0.009 |

Table 2.3
Preferred and optimal stride rates at the beginning and end of the hour run.

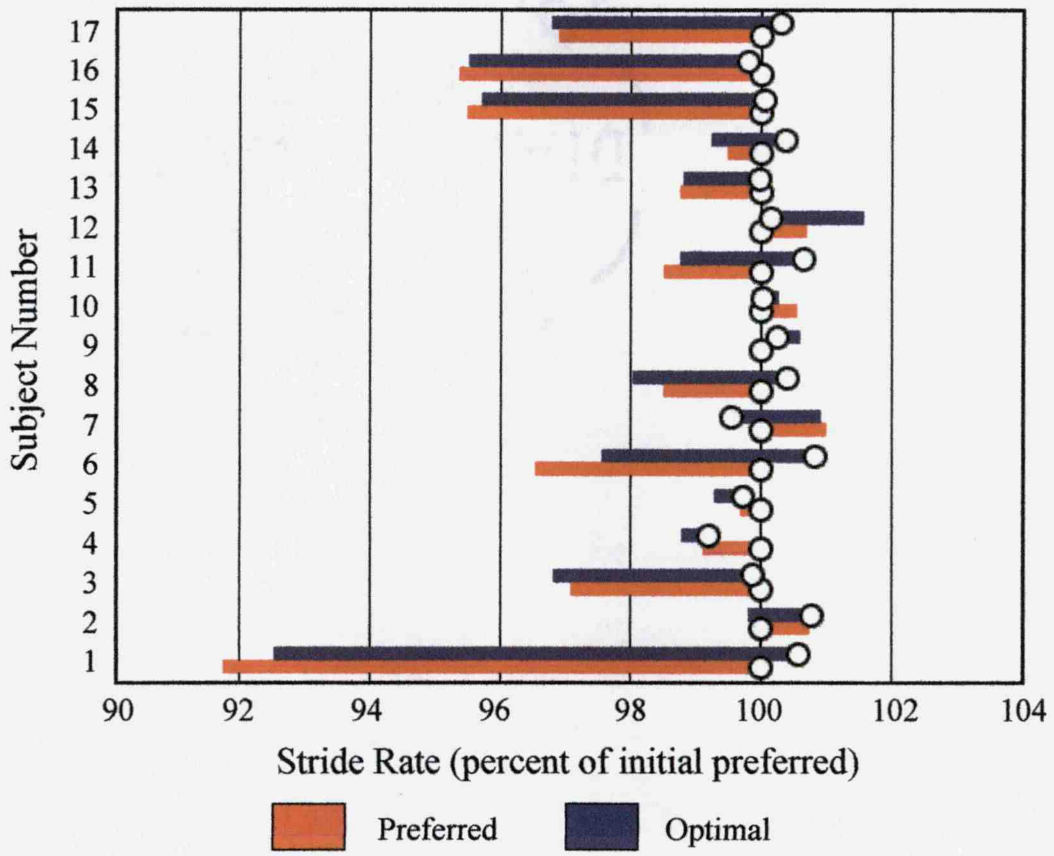

Figure 2.8
Percent changes in preferred and optimal stride rates. Open circles represent initial rates. Colored lines extend to final rates.

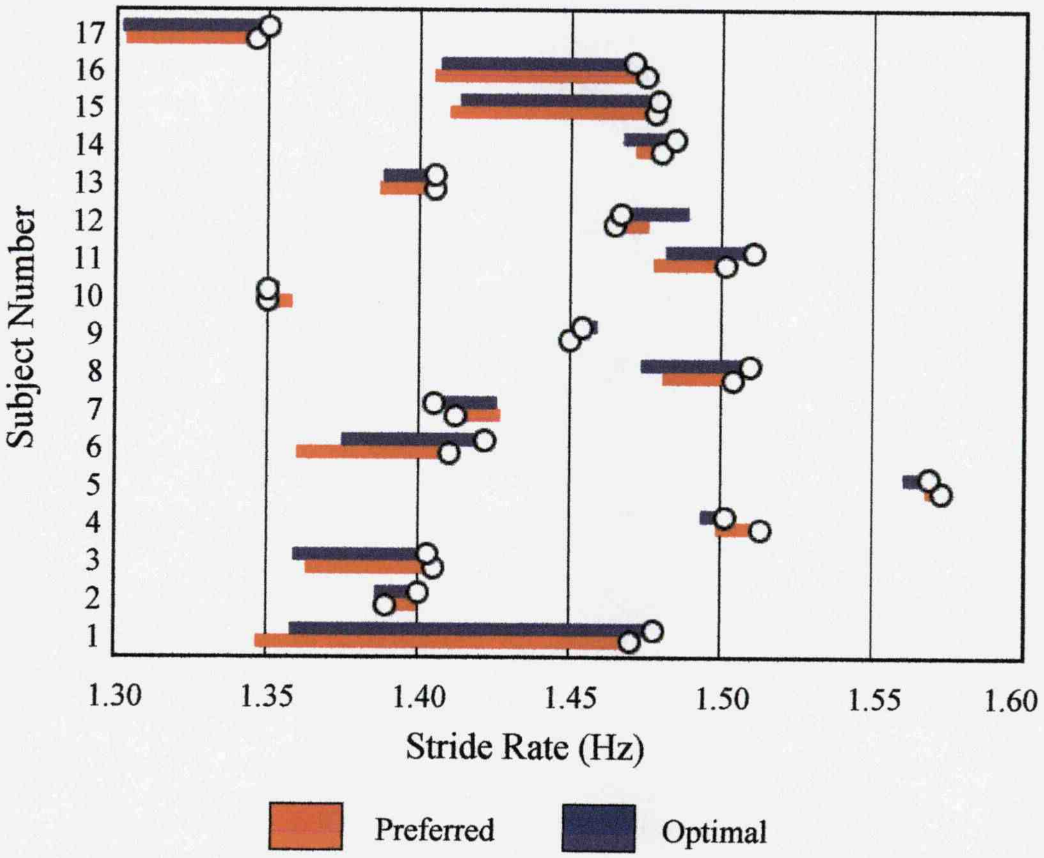

Figure 2.9
Raw data of changes in preferred and optimal stride rates. Open circles represent initial rates. Colored lines extend to final rates.

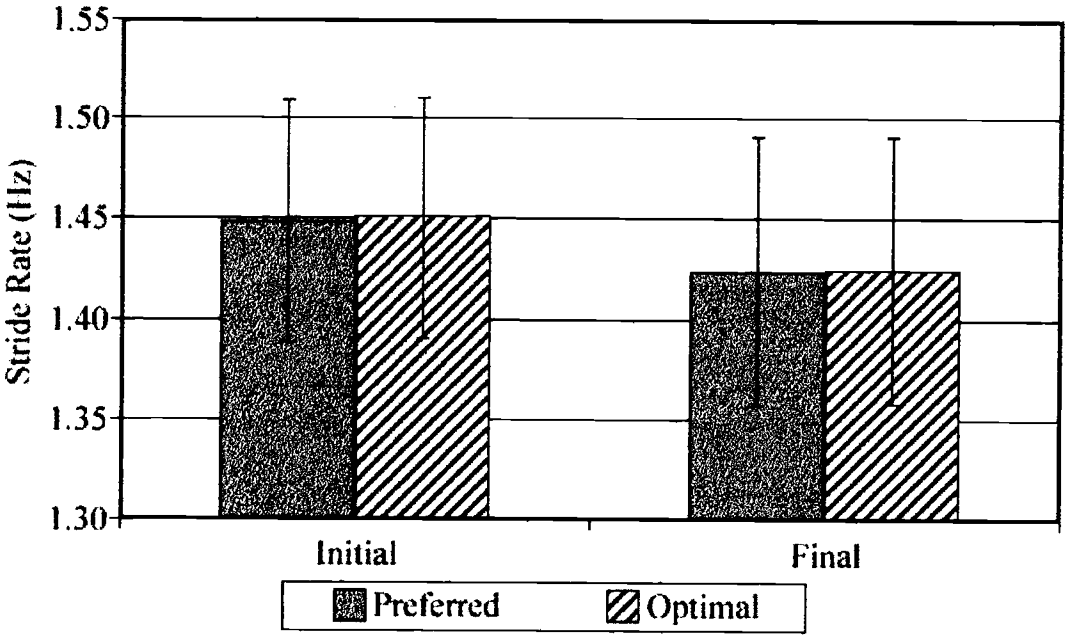

Figure 2.10
Mean stride rate with standard deviation between subjects.

was 1.1 kN/m during initial and final readings. Vertical stiffness decreased in 11 of the 17 subjects (Table 2.4). Stiffness increases in six subjects averaged 0.5 kN/m. No significant difference was observed between initial and final stiffness using a paired *t*-test (p=0.10).

***Decreases in preferred stride rate versus decreases in stiffness.*** While a regression line showed the expected trend (Δpercent initial preferred rate = 0.2674*Δpercent initial stiffness - 0.0145, $R^2$=0.12, (Figure 2.11)), so much variability existed throughout the data that no significant relationship was determined.

| | **Vertical Stiffness (kN/m)** | | |
|---|---|---|---|
| **Subject** | **Initial** | **Final** | **Change** |
| 1 | 34.9 | 35.1 | 0.1 |
| 2 | 38.0 | 34.8 | -3.2 |
| 3 | 42.2 | 43.0 | 0.8 |
| 4 | 25.0 | 26.2 | 1.2 |
| 5 | 32.8 | 31.6 | -1.2 |
| 6 | 35.9 | 34.2 | -1.7 |
| 7 | 41.2 | 40.0 | -1.2 |
| 8 | 35.8 | 36.0 | 0.3 |
| 9 | 25.6 | 24.3 | -1.3 |
| 10 | 38.0 | 36.7 | -1.3 |
| 11 | 34.2 | 33.3 | 0.8 |
| 12 | 34.2 | 33.2 | -1.1 |
| 13 | 33.4 | 34.0 | 0.6 |
| 14 | 32.6 | 32.0 | -0.7 |
| 15 | 43.6 | 39.1 | -4.6 |
| 16 | 40.6 | 38.1 | -2.5 |
| 17 | 44.1 | 43.7 | -0.4 |

| | | | |
|---|---|---|---|
| **Average** | 36.0 | 35.0 | -1.0 |
| **Std Dev** | 5.5 | 5.1 | |

Table 2.4
Vertical stiffness at the beginning and end of the hour run.

Average standard deviation for within subject stiffness measurements based upon ten steps was 4.5% of the mean and for thirty second preferred stride rate measurements was 0.9% of the mean. The average decrease in preferred stride rate was 1.5% while the average decrease in vertical stiffness was 1.0%.

Six of the 17 subjects had small increases in vertical stiffness between the initial and final measurements. These subjects had little or no change in preferred stride rate. Four other subjects had small increases in preferred stride rate, but decreases in vertical stiffness. However, the stiffness variability observed overlaps with zero in all of these cases.

## *DISCUSSION*

***Changes in preferred stride rate.*** Eight of the 17 subjects showed preferred stride rate decreases of greater than one percent. The average decrease of these eight subjects was 3.4%. A 3.4% change in stride rate is very noticeable. However, during extended running, stride rate changes usually occurred over a long period of time and subjects did not realize their preferred stride rate was changing. Three subjects had increases in stride rate over the course of the run, but they were quite small (less than one percent).

The question of stride rate changing is not as simple as whether it increased or decreased. There is also the factor of when the changes occurred. As was shown in Figures 2.6 and 2.7, subjects who decreased stride rate over time had a wide variety of methods of altering preferred stride rate. Some showed a systematic decrease with time, others decreased only after a period of time through the run, then maintained that decrease. It remains unclear why preferred stride rate changes occurred and why subjects who changed followed such different trends for the observed changes. Perhaps subjects were trying to economize their running technique, which would indicate preferred stride rate is just following optimal stride rate.

| Subject | Running speed (m/s) | Initial percent of max $\dot{V}O_2$ | Final percent of max $\dot{V}O_2$ |
|---|---|---|---|
| 1 | 4.03 | 82.5% | 78.3% |
| 2 | 4.10 | 77.6% | 77.4% |
| 3 | 3.73 | 80.5% | 82.1% |
| 4 | 3.42 | 69.7% | 73.0% |
| 5 | 3.73 | 84.5% | 86.4% |
| 6 | 3.82 | 74.0% | 87.0% |
| 7 | 4.23 | 88.6% | 87.6% |
| 8 | 3.83 | 81.1% | 80.6% |
| 9 | 3.38 | 66.7% | 66.9% |
| 10 | 3.30 | 81.9% | 88.1% |
| 11 | 3.80 | 64.1% | 69.5% |
| 12 | 2.98 | 72.9% | 76.4% |
| 13 | 4.28 | 76.1% | 77.8% |
| 14 | 4.28 | 77.9% | 79.3% |
| 15 | 3.83 | 83.0% | 85.9% |
| 16 | 4.28 | 76.1% | 77.1% |
| 17 | 4.60 | 86.3% | 88.1% |
| Average | 3.86 | 77.9% | 80.1% |
| Standard Deviation | 0.42 | 6.8% | 6.5% |

Table 2.5
Summary of metabolic changes during the one hour run.

***Changes in optimal stride rates.*** Changes in optimal stride rates were similar to those found in preferred rates. The same eight subjects that had greater than one percent decreases in preferred stride rate also had greater than one percent decreases in optimal stride rate. The direction of optimal stride rate changes was equal to preferred changes in all but one case where the changes were almost zero.

Muscle temperature, hormone levels, energy sources, EMG activity, and pH are all altered from the beginning to end of fatiguing runs (2, 10, 14, 18). During the stance phase of running, energy is stored in muscles and tendons during the eccentric phase, then released during the concentric phase (9). A simple mass-spring model describes this motion quite well. This model describes the center of mass of the runner being attached to the ground by a spring during the stance phase of running. The main component of the spring is the leg (although other parts of the body are also incorporated). Since muscle state is altered by fatigue, elastic storage of the muscle may also change. Leg stiffness has been associated with stride rate (13). The decreased stride rate commonly seen in fatigued runners may be associated with decreased leg stiffness which may be why optimal stride rate changes.

***Similarity of preferred and optimal stride rate.*** Experienced runners appear to self-optimize stride rate throughout a fatiguing run. Due to the relatively flat parabolic shape of the $\dot{V}O_2$ versus stride rate relationship, a range of stride rate values near optimal would result in a relatively small increase in oxygen uptake. All subjects were observed to prefer stride rates in this very narrow range even when their optimal stride rate changed throughout the run.

Means, standard deviations, and confidence intervals were almost exactly equal between preferred and optimal stride rates within each measurement stage. Sufficient power existed to detect small differences between preferred and optimal stride rates. The largest difference between preferred and optimal stride rates for any subject was 1.0%. Assuming this most extreme case of preferred and optimal stride rates being 1.0% different, the increase in oxygen uptake due to this deviation would have been 0.103% (0.038 ml/kg/min). The average positive difference between preferred and optimal stride rates of 0.36% gives an increase in oxygen uptake of only 0.013% (0.005 ml/kg/min). Differences in preferred and optimal stride rates initially and finally were very similar leading to the conclusion that with this small increase in oxygen uptake, experienced runners self-optimize stride rate when rested and when fatigued.

A range of stride rates can be found where oxygen uptake is not increased very much as shown in Figure 2.13. This gives even more strength to the argument that runners naturally self-optimize stride rate. The data showed every subject to be well within a range of stride rates that the maximum increase in oxygen uptake due to deviating from optimal stride rate was less than 0.103 % (approximately 0.038 ml/kg/min). Each subject's preferred stride rate was very close to the minimum value of the polynomial curve. Even if they were slightly further away than was measured, they would still have shown very small increases in oxygen uptake due to this deviation from optimal. In order to increase oxygen uptake considerably, subjects would need to deviate from optimal stride rate by a large amount.

***Changes in vertical stiffness.*** While decreases in vertical stiffness was observed in 11 of 17 subjects, the decrease in stiffness was small compared with the within subject standard deviation. In order to find a statistically significant decrease in vertical stiffness between initial and final readings, many more subjects would be required. Sufficient power to detect a decrease in vertical stiffness was lacking in the current design.

***Stride rate versus vertical stiffness.*** Stride rate was expected to be associated with vertical stiffness. While the expected trend for stride rate versus vertical stiffness was found, the variability explained by the analysis was minimal ($R^2=0.12$). The standard deviation for within subject stiffness measurements was over three times the average change in stiffness. Figure 2.11 demonstrates how the changes in stride rate and stiffness throughout the run were quite small compared to the inter and intra-subject variability. It is possible that the hypothesis of preferred stride rate decreasing with decreasing stiffness is incorrect. However, the results from this study are inconclusive. More subjects may have created enough power to obtain a significant finding, but it seems likely that vertical stiffness changes alone do not determine a substantial portion of stride rate changes occurring with fatigue.

***Difficulty of the run.*** Average oxygen uptake while running at preferred stride rate was 77% during the initial stage and 79% during the final stage (Figure

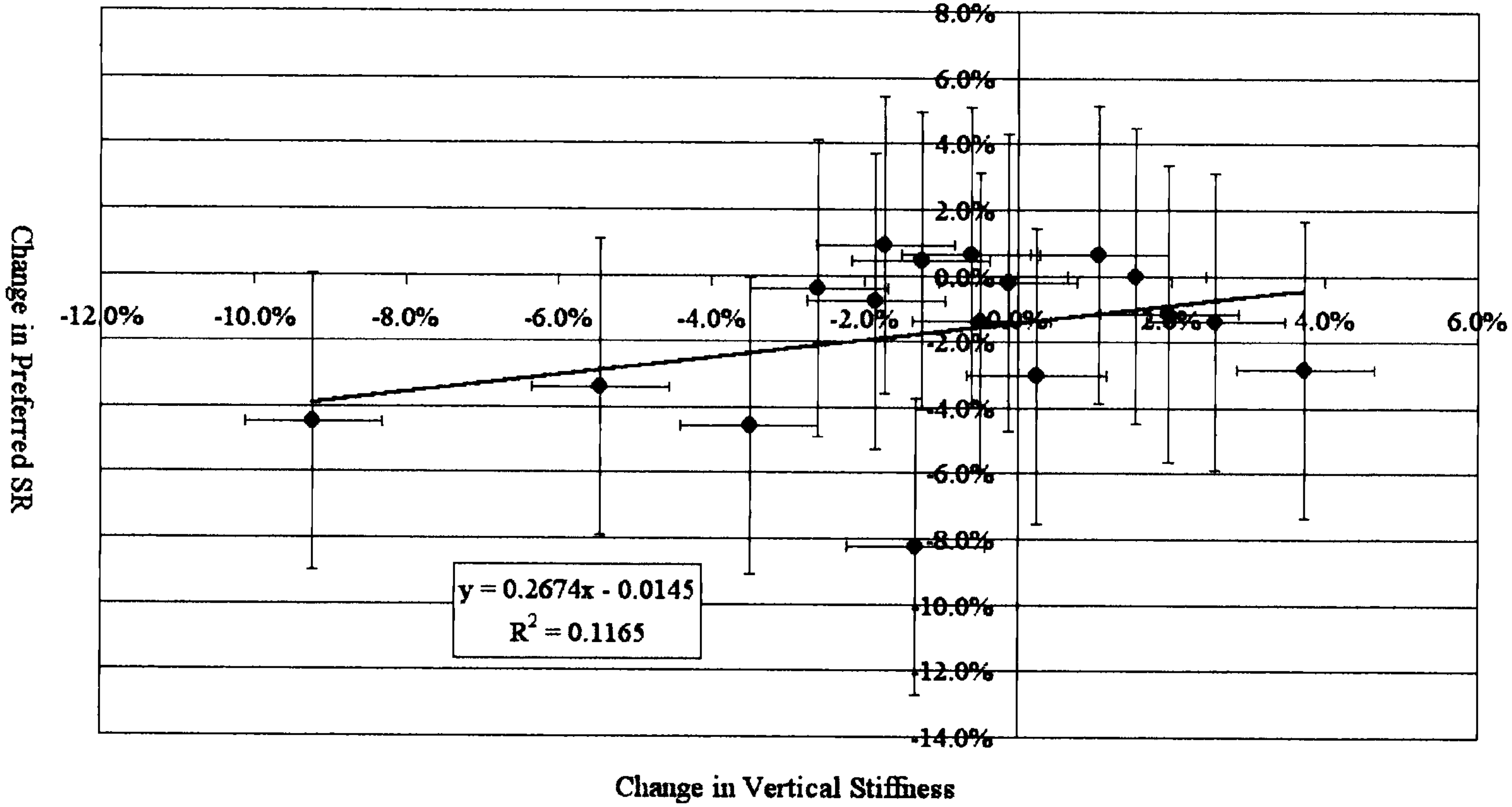

Figure 2.11
Regression line of percent change in stride rate versus percent change in vertical stiffness. Error bars represent one within subject standard deviation.

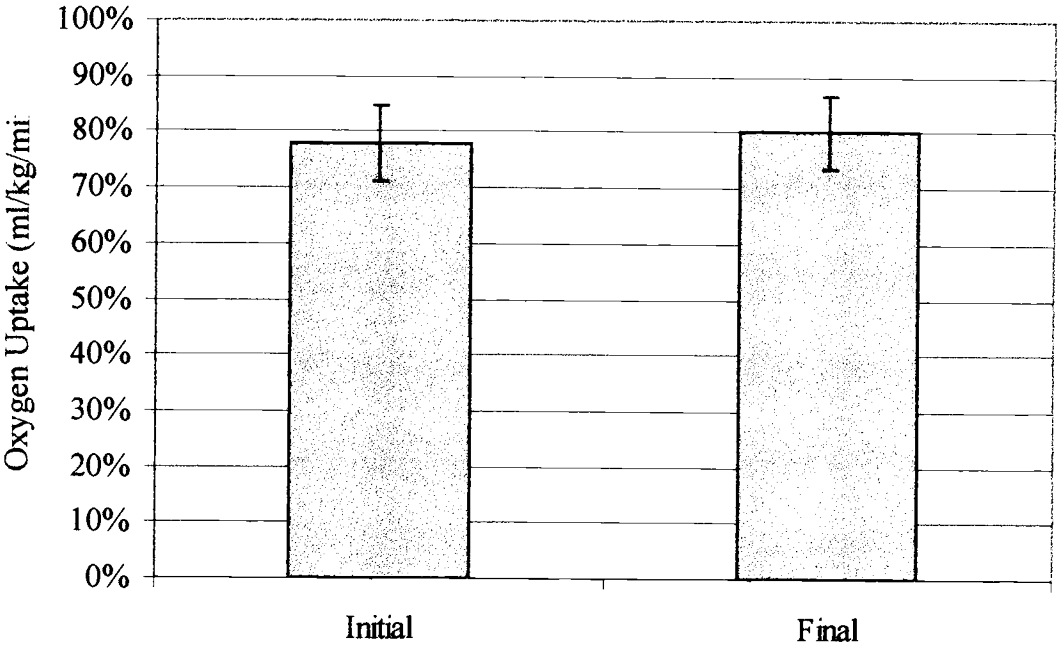

Figure 2.12
Mean initial and final oxygen uptake values.

2.12). Subjects described being able to continue running for an average time of 12 minutes beyond the hour (see Table 2.5). It was expected that stride rate decreases would be found due to fatigue. This did not occur in every subject and no relationship appeared between subject's estimation of how much longer they could have continued to run and whether or not they showed decreases in stride rate.

***Accommodation to new stride rates.*** Some question arose as to whether maintaining an altered stride rate for an extended period of time would lead to accommodation and a new optimal stride rate. Perhaps if one were to run at four percent above the preferred rate for 10 minutes, this altered stride rate would

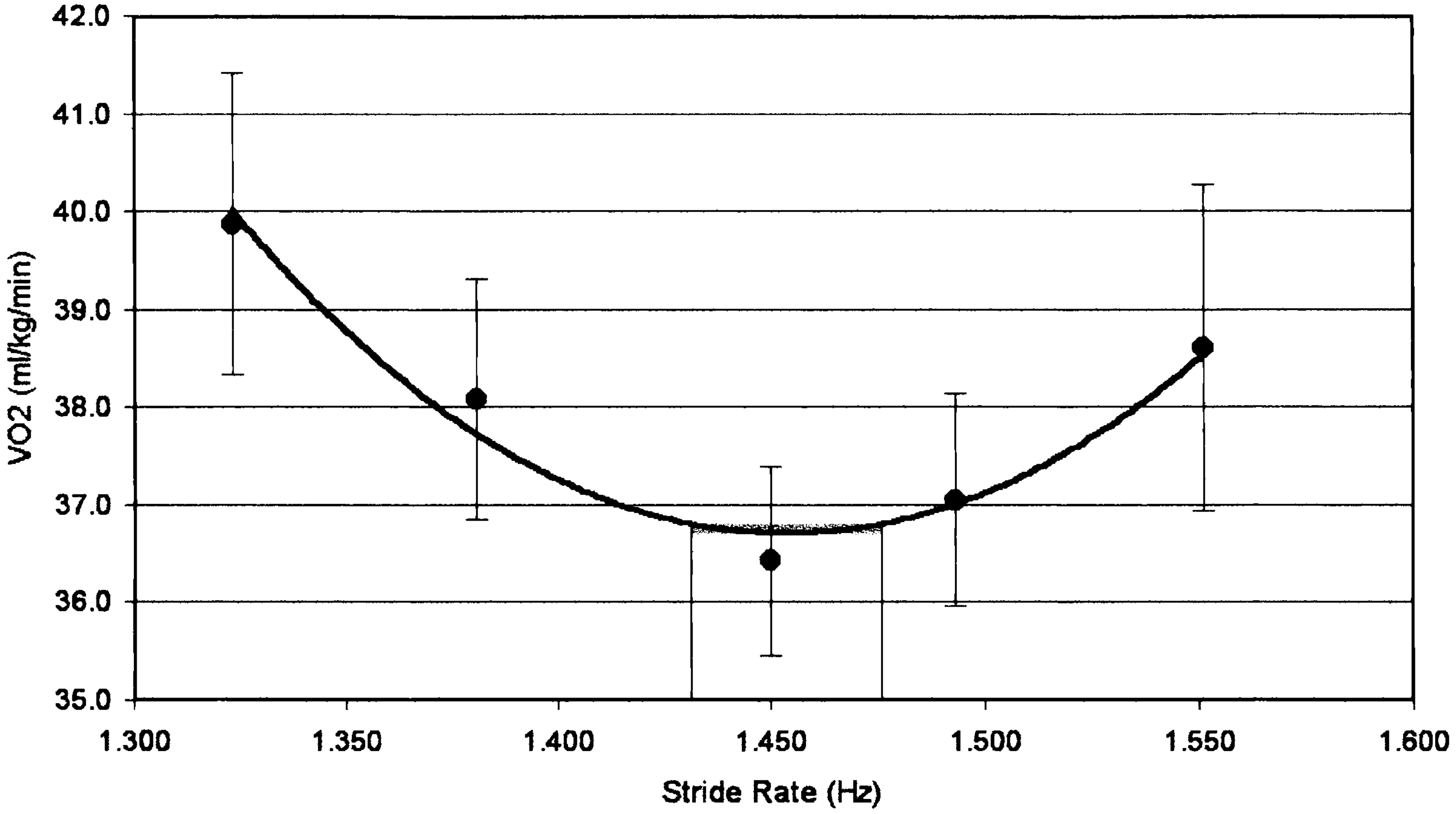

Figure 2.13
Example of range of stride rates that would correspond with less than 0.2% increase in oxygen uptake.

| Subject Number | Capacity to continue (min) |
|---|---|
| 1 | 10 |
| 2 | 7 |
| 3 | 6 |
| 4 | 6 |
| 5 | 5 |
| 6 | 20 |
| 7 | 30 |
| 8 | 15 |
| 9 | 10 |
| 10 | 10 |
| 11 | 30 |
| 12 | 10 |
| 13 | 3 |
| 14 | 30 |
| 15 | 20 |
| 16 | 25 |
| 17 | 0 |

Table 2.6
Capacity of subjects to continue running. Length of time subjects felt they could have maintained data collection run pace past one hour.

become optimal. This idea was not tested as part of the study. However, data were taken from one runner using the following protocol to see whether 10 minutes of altered stride rate may lead to oxygen uptake increasing with a new stride rate, but then decreasing to the oxygen uptake measured at the original preferred rate.

1. Five minutes at preferred stride rate.
2. Ten minutes at minus eight percent of initial preferred stride rate.
3. Five minutes at initial preferred stride rate.

4. Ten minutes at plus eight percent of initial preferred stride rate.
5. Five minutes at initial preferred stride rate.

Some cardiovascular drift was seen throughout the run, but the trends shown appear to show no accommodation occurring (Figure 2.14). Oxygen uptake at preferred stride rate followed a slight upward drift. When returning to preferred stride rates, oxygen uptake always returned to this slope. Altered stride rates continued a near equal slope, but had a higher intercept demonstrating increased oxygen uptake. If accommodation was taking place, the slope of the altered rates would be expected to decrease over time. Also, oxygen uptake at the preferred rate would increase above the line representing cardiovascular drift when shifts were made from altered rates back to preferred rates.

***Cardiovascular drift.*** Various theories exist as to the cause of cardiovascular drift (3). Changes in vertical stiffness provide a mechanical reason for cardiovascular drift. When muscles become fatigued, a reduction in isometric peak force occurs (10), hamstring peak torque creation is decreased (18), and maximum shortening velocity is reduced (10). While the muscles are probably not required to reach peak isometric force or maximum shortening velocity in running, these muscular limitations are evidence of physical changes which may lead to altered technique. Changes in the force-frequency relationship also occur in fatigued muscle. In a fatigued state, activation frequency must be increased to maintain force production (2). Pinniger found that EMG duration increases as runners become fatigued, starting earlier and finishing later around the stance phase (18). Slight technique changes were associated with the increases in EMG duration in Pinniger's study, including a decrease in stride rate. One result of these muscular changes may be a decreased ability to maintain a stiff leg. If vertical stiffness changes, optimal stride rate may also change due to the association between the two (13) leading to an increase in oxygen uptake due to the altered condition of the muscles and tendons that affect the "leg spring".

***Strengths and limitations.*** Stride rate measurements were very accurate due to the instrumentation used. Measured stride rates were averaged over 30 seconds with the data from the instrumented treadmill which was sampling at 500 Hz. These accurate measurements also provided step-by-step information on stride rate variability.

A one-hour run is fatiguing for most runners, no matter how fast their pace is. Even if the estimated pace to place runners near exhaustion was inaccurate, some fatigue effects most likely occurred.

The metronome used to help subjects run at altered stride rates was set based upon the timing of ten preferred rate strides. These altered rates only represented plus and minus four and eight percent if the ten stride measurement of the preferred rate was accurate. In all cases, the preferred rate ended up between what was estimated as plus and minus four percent. However, it was very common that during the first two-minute segment of optimal stride rate measurements (where subjects were running at their preferred rate), preferred stride rate would be slightly different than the ten stride measurement. The calculation of optimal

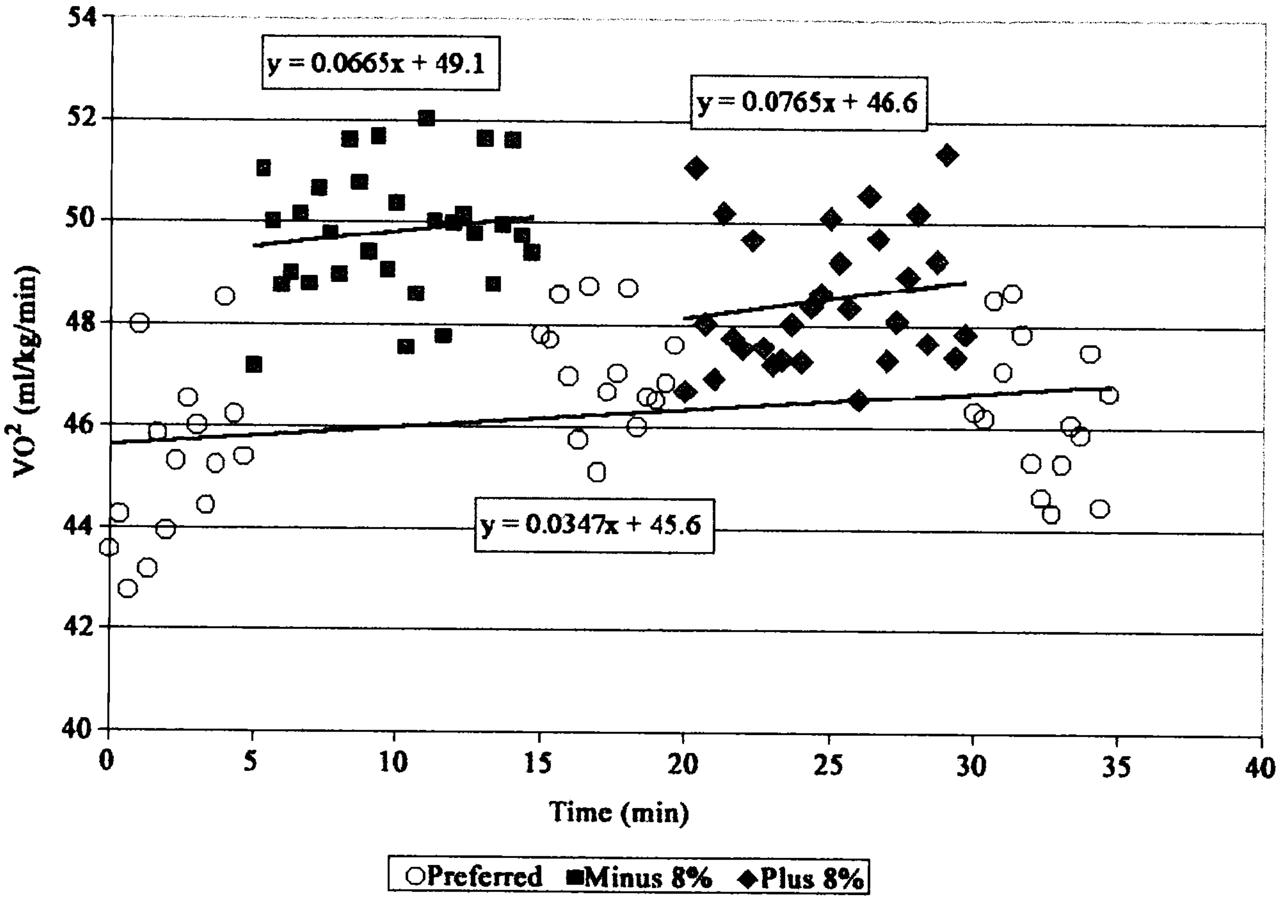

Figure 2.14
Test for altered stride rate accommodation.

stride rate should not have been affected by this limitation substantially and perhaps not at all. Five distinct data points existed to base a polynomial fit, and in each case, a minimum value of the curve created was found.

Two preferred stride rate measurements went into each of the two measurement stages. The first, was a ten-stride measurement that was used in estimating the metronome's cadence. The second was a thirty-second measurement that took place during the first two-minute segment where subjects were running at their preferred rate without the aid of a metronome. There were times when preferred stride rate from these two measurements did not match up exactly. This was perhaps due to having the mouthpiece and headgear for oxygen uptake collection in, anxiety of knowing stride rate alterations were coming, the short rest while the mouthpiece and headgear were being placed, or the different lengths of preferred rate measurement resulting in a more accurate value when the collection period was 30 seconds rather than only ten strides.

These differences were not be a problem in calculating preferred and optimal stride rates for the hypotheses of this project because the more accurate measurement was the one taken into analysis. However, if the reason for different values was subjects having the mouthpiece and headgear on, the accuracy of some of the stride rate profiles describing preferred stride rate changes throughout the run could be compromised.

Five of the 17 subjects in the study were female. Average preferred stride rates were higher for the females than the males, 1.495 and 1.411 respectively.

Average running speed was 3.4 m/s (7:47 min/mile) for the women and 4.0 m/s (6:42 min/mile) for the men. The differences in running speed were expected and should not make a difference to the findings as long as the chosen speeds placed the runners near exhaustion. The women ran an average of 75.4% $\dot{V}O_2$ max while the men averaged 80.5%. This was somewhat unexpected since the runs were normalized according to max $\dot{V}O_2$ percent. After completing the run, subjects were asked how many more minutes they could have completed at the same pace. The women estimated an average of 12.2 minutes and the men estimated 14.7, so it appears that while speeds and percent of $\dot{V}O_2$ max were different the fatigue states of the runners were similar at the end of the run (assuming males and females estimate the same). A result of this difference of percent of $\dot{V}O_2$ max could have been less fatigue in the women, but there was no way to determine this with the measurements taken.

No direct physiological measurements of fatigue were taken. However, three indications of fatigue existed in the data. First, previously noted changes in fatigue were seen in some subjects including, cardiovascular drift and preferred stride rate decreases. Second, subjects were running at an average of 79% max $\dot{V}O_2$. In previous studies, this seems like a typical value to bring subjects to voluntary exhaustion after one hour of running (11, 20, 21). Finally, after each data collection run was completed, subjects indicated how many more minutes they felt they could have continued. The average of these times was 13.9 minutes which gives the impression that the average run speed was very close to optimal to obtain the desired fatigue levels.

Treadmill running is slightly different than overground running. During overground running, surfaces are different and speed can be altered more easily. This study required treadmill running due to the instrumentation. While some differences would likely be seen in overground running, the concepts determined in this study should still apply.

***Conclusion.*** Experienced distance runners are capable of stride rate and length self-optimization during all stages of near-maximal effort one-hour runs. Although optimal stride rate sometimes changes, usually decreasing, runners are capable of altering their preferred rate to match the new optimal rate. A range of stride rates near optimal will provide minimal increases in oxygen uptake. All of the measured preferred rates were in a range where the maximum increase in oxygen uptake due to not being exactly self-optimized was less than 0.142 ml/kg/min. However, stride rates further from optimal result in substantially increased metabolic cost.

Further research must be completed to find out whether an association exists between changing vertical stiffness and changing stride rate. High variability in the measurements compared with the small changes observed resulted in non-significant findings.

## *REFERENCES*

1. Bates, B. T. and L. R. Osternig. Fatigue effects in running. *Journal of Motor Behavior.* 9:203-207, 1977.

2. Binder-Macleod, S. A., S. Lee, A. D. Fritz, and L. J. Kucharski. New look at force-frequency relationship of human's skeletal muscle: Effects of fatigue. *Journal of Neurophysiology.* 79:1858-1868, 1998.

3. Brooks, G. A., T. D. Fahey, T. P. White, and K. M. Baldwin. *Exercise physiology: Human bioenergetics and its applications.* Mountain View, CA: Mayfield Publishing, 2000.

4. Boutellier, U., Giezendanner, D., Cerretelli, P., & Di-Prampero, P.E. After effects of chronic hypoxia on $O_2$ kinetics and on $O_2$ deficit and debt. *European Journal of Applied Physiology.* 53:87-91, 1984.

5. Candau, R. et al. Energy cost and running mechanics during a treadmill run to voluntary exhaustion in humans. *European Journal of Applied Physiology.* 77:479-485, 1998.

6. Cavanagh, P. R. and K. R. Williams. The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise.* 14:30-35, 1982.

7. Cerretelli, P., Shindell, D., Pendergast, D.P., Di-Prampero, P.E., & Rennie, D.W. Oxygen uptake transients at the onset and offset of arm and leg work. *Respiration Physiology.* 30:81-97, 1977.

8. Costill, D. L. The relationship between selected physiological variables and distance running performance. *Journal of Sports Medicine.* 7:41-44, 1967.

9. Dalleau G., A. Belli, M. Bourdin, J. R. Lacour. The spring-mass model and the energy cost of treadmill running. *European Journal of Applied Physiology and Occupational Physiology.* 77:257-263, 1998.

10. De Haan, A., D. A. Jones, and A. J. Sargeant. Changes in velocity of shortening, power output and relaxation rate during fatigue of rat medial gastrocnemius muscle. *European Journal of Physiology.* 413:422-428, 1989.

11. Dutto, D. *Leg spring model related to muscle activation, force, and kinematical patterns during endurance running to voluntary exhaustion.*

Unpublished doctoral dissertation, Oregon State University, Corvallis, OR. 2000.

12. Elliott, B and T. Ackland. Biomechanical effects of fatigue on 10,000 meter running technique. *Research Quarterly for Exercise and Sport.* 52:160-166, 1981.

13. Farley C. T. and O. Gonzalez. Leg stiffness and stride frequency in human running. *Journal of Biomechanics.* 29:181-186, 1996.

14. Farrell, P. A., J. H. Wilmore, E. F. Coyle, J. E. Billing, and D. L. Costill. Plasma lactate accumulation and distance running performance, *Medicine and Science in Sports and Exercise.* 11:338-344, 1979.

15. Fewster, J. B. *The role of musculoskeletal forces in the human walk-run transition.* Unpublished masters thesis, Oregon State University, Corvallis, OR., 1996.

16. Foster, C., D. L. Costill, J. T. Daniels, and W. J. Fink. Skeletal muscle enzyme activity, fiber composition and $\dot{V}O_{2\,max}$ in relation to distance running performance. *European Journal of Applied Physiology.* 39:73-80, 1978.

17. Morgan, D. W., F. D. Baldini, P. E. Martin, and W. M. Kohrt. Ten kilometer performance and predicted velocity at $\dot{V}O_2$ max among well-trained male runners. *Medicine and Science in Sports and Exercise.* 21:78-83, 1989.

18. Pinniger, G. J., J. R. Steele, and H. Groeller. Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Medicine and Science in Sports and Exercise.* 32:647-653, 2000.

19. Powers, S., S. Dodd, and R. Garner. Precision of ventilatory and gas exchange alterations as a predictor of the anaerobic threshold. *European Journal of Applied Physiology.* 52:173-177, 1984.

20. Tokmakidis S. P. and K. A. Volaklis. Pre-exercise glucose ingestion at different time periods and blood glucose concentration during exercise. *International Journal of Sports Medicine.* 216:453-457, 2000.

21. White J. A., D. Pomfret, S. Rennie, C. Gissane, J. Wong, M. Ford. Fluid replacement needs of well-trained male and female athletes during indoor and outdoor steady state running. *Journal of Science and Medicine in Sport.* 13:131-142, 1998.

22. Williams, K. R, R. Snow, and C. Agruss. Changes in distance running kinematics with fatigue. *Medicine and Science in Sports and Exercise*. 20:S49, 1988.

# CHAPTER 3
# SUMMARY

Optimizing technique is of great importance to distance runners for minimizing injury risk, improving endurance, and maximizing racing performance. One aspect of technique that can easily be manipulated is stride rate, the number of strides taken per second. While runners are capable of utilizing a relatively wide range of stride rates, they must determine which stride rate will be most effective benefit. During extended running, preferred stride rate changes for many runners. When running at a near-maximal sustainable effort for one hour, this study showed that runners naturally select a stride rate which minimizes metabolic cost not only near the beginning of the run, but also near the end when very fatigued. This optimization was observed even when a substantial change of stride rate occurred with fatigue.

Seventeen subjects completed a one-hour near-maximal effort run on a treadmill at a fixed speed slightly slower than each individual's 10 km race pace. After the first five minutes, preferred and optimal stride rates were measured. Ground reaction force data from an instrumented treadmill were used to determine preferred stride rate averaged over ten strides. Runners completed five two-minute segments of running at preferred stride rate, 4% above, 4% below, 8% above and 8% below their preferred rate. Oxygen uptake was measured during the second minute of each two-minute segment. Fitting a second-degree polynomial through the oxygen uptake versus stride rate data points provided a minimum value for oxygen uptake from which optimal stride rate was determined. The runners then continued without having stride rate manipulated for 35 minutes, (50 minutes elapsed from the beginning of the run). The final ten minutes involved a manipulated stride rate stage like that occurring near the beginning of the run but with a new randomization of order for the altered stride rates.

Two-way ANOVA showed a significant difference between initial and final readings of optimal stride rate. No significant differences were observed between optimal and preferred stride rates. The average decrease in optimal stride rate from the beginning to the end of the run was 1.8%. About half of the subjects decreased preferred and optimal stride rate over the course of the hour run while half showed little or no change. The average difference of preferred and optimal stride rate was 0.39%. This small deviation from optimal stride rate resulted in an average increase in oxygen uptake of 0.14% (about 0.5 ml/kg/min) over optimal. A range of stride rates existed where oxygen uptake would not be increased substantially, however, if one deviates from this range oxygen uptake increases rapidly. All subjects were well within this range during both measurement stages of the run.

Vertical force was measured using an instrumented treadmill. The peak value of vertical force during the stance phase of running divided by the displacement of the center of mass of the runner provides a stiffness value for the body. This "vertical" stiffness value is mainly used to describe how the leg is reacting to the loads placed upon it during stance. As muscles become fatigued, their ability to react quickly to these loads is compromised, perhaps resulting in greater compression of the leg which could lead to decreased stiffness. Stride rate changes have previously been associated with vertical stiffness changes. However, in the current study, changes in stride rate and vertical stiffness were small; no strong relationship was observed (R=0.35).

Experienced runners have demonstrated the capability to self-optimize stride rate at the beginning of a run and when very fatigued near the end of an hour run. This consistent ability was observed for runners with substantial shifts of stride rate with fatigue as well as for runners with no change of stride rate with fatigue. The ability to self-optimize despite changing optimal rates helps runners maintain given speeds for longer times than would be possible if constant stride rate were maintained for the full time.

Some subjects in this study demonstrated decreases in preferred stride rate across the hour run while others did not change. It is unclear what leads to rate decreases for some runners but not others. Vertical stiffness may be influenced by fatigue and this may lead to decreased stride rate, however the experimental design was not sensitive enough to determine or rule out this explanation. Why fatigue would affect leg stiffness of some runners but not others, remains unknown.

# BIBLIOGRAPHY

Bates, B.T. & Osternig, L.R. (1977). Fatigue effects in running. *Journal of Motor Behavior*, **9**, 203-207.

Binder-Macleod, S.A., Lee SCK, Fritz A.D., and Kucharski L.J. (1998). New look at force-frequency relationship of human's skeletal muscle: Effects of fatigue. *Journal of Neurophysiology*, **79**, 1858-1868.

Brooks, G.A., Fahey, T.D., White, T.P., & Baldwin, K.M. (2000). *Exercise physiology: Human bioenergetics and its applications.* Mountain View, CA: Mayfield Publishing.

Boutellier, U., Giezendanner, D., Cerretelli, P., & Di-Prampero, P.E. (1984). After effects of chronic hypoxia on O2 kinetics and on O2 deficit and debt. *European Journal of Applied Physiology*, **53**, 87-91.

Candau, R. et al. (1998). Energy cost and running mechanics during a treadmill run to voluntary exhaustion in humans. *European Journal of Applied Physiology*, **77**, 479-485.

Cavanagh, P.R. & Williams, K.R. (1982). The effect of stride length variation on oxygen uptake during distance running. *Medicine and Science in Sports and Exercise*, **14**, 30-35.

Cerretelli, P., Shindell, D., Pendergast, D.P., Di-Prampero, P.E., & Rennie, D.W. (1977). Oxygen uptake transients at the onset and offset of arm and leg work. *Respiration Physiology*, **30**, 81-97.

Costill, D.L. (1967). The relationship between selected physiological variables and distance running performance. *Journal of Sports Medicine*, **7**, 41-44.

Dalleau G, Belli A, Bourdin M, Lacour JR. (1998). The spring-mass model and the energy cost of treadmill running. *European Journal of Applied Physiology and Occupational Physiology*. **77**, 257-263.

De Haan, A., Jones, D.A., & Sargeant, A.J. (1989). Changes in velocity of shortening, power output and relaxation rate during fatigue of rat medial gastrocnemius muscle. *European Journal of Physiology*, **413**, 422-428.

Dutto, D. (2000). *Leg spring model related to muscle activation, force, and kinematical patterns during endurance running to voluntary exhaustion.* Unpublished doctoral dissertation, Oregon State University, Corvallis, OR.

Elliott, B. & Ackland, T. (1981). Biomechanical effects of fatigue on 10,000 meter running technique. *Research Quarterly for Exercise and Sport*, **52**, 160-166.

Farley C.T., Gonzalez O. Leg stiffness and stride frequency in human running. J Biomech. 1996 Feb;29(2):181-6.

Farrell, P.A., Wilmore, J.H., Coyle, E.F., Billing, J.E., & Costill, D.L. (1979). Plasma lactate accumulation and distance running performance, *Medicine and Science in Sports and Exercise*, **11**, 338-344.

Fewster, J.B. (1996). *The role of musculoskeletal forces in the human walk-run transition.* Unpublished masters thesis, Oregon State University, Corvallis, OR.

Foster, C., Costill, D.L., Daniels, J.T., & Fink, W.J. (1978). Skeletal muscle enzyme activity, fiber composition and $\dot{V}O_{2\,max}$ in relation to distance running performance. *European Journal of Applied Physiology*, **39**, 73-80.

Lloyd, B.B. (1966). The energetics of running: an analysis of world records. *Advanced Science*, **22**, 515-530.

Morgan, D.W., Baldini, F.D., Martin, P.E., & Kohrt, W.M. (1989). Ten kilometer performance and predicted velocity at $\dot{V}O_{2\,max}$ among well-trained male runners. *Medicine and Science in Sports and Exercise*, **21**, 78-83.

Pinniger, G.J., Steele, J.R., & Groeller, H. (2000). Does fatigue induced by repeated dynamic efforts affect hamstring muscle function? *Medicine and Science in Sports and Exercise*, **32**, 647-653.

Powers, S., Dodd, S., & Garner, R. (1984). Precision of ventilatory and gas exchange alterations as a predictor of the anaerobic threshold. *European Journal of Applied Physiology*, **52**, 173-177.

Tokmakidis S.P. & Volaklis K.A. (2000). Pre-exercise glucose ingestion at different time periods and blood glucose concentration during exercise. *International Journal of Sports Medicine*, **21**, 453-457.

White J.A., Pomfret D., Rennie S., Gissane C., Wong J., & Ford M.. (1998). Fluid replacement needs of well-trained male and female athletes during indoor and outdoor steady state running. *Journal of Science and Medicine in Sport*, **1**, 131-142.

Williams, K.R, Snow, R., & Agruss, C. (1988). Changes in distance running kinematics with fatigue. *Medicine and Science in Sports and Exercise*, **20**, S49.

# APPENDICES

## APPENDIX A

## HEALTH HISTORY QUESTIONNAIRE

**Full Name:** ______________________________ **Date:** ___/___/___

**1.Age:** _____ **Date of Birth:** ___/___/___ **I.D. #:** ________

The purpose of this questionnaire is to obtain information regarding your health necessary for the researchers in assisting you with your participation in this study. Please answer all questions to the best of your knowledge. Circle the correct answers.

1. Do you have high blood pressure? YES NO
2. Do you have high blood cholesterol? YES NO
3. Do you currently smoke? YES NO
4. Are you a former smoker? YES NO
5. If so, when did you quit? ______________
6. Have you ever had a heart attack? YES NO
7. Have you ever had chest pain (angina)? YES NO

8. Have any of your blood relatives had heart disease, heart surgery, or angina?
YES NO
9.
10. If so, what is the relation? _________What did they have?___________
11. Are you diabetic? YES NO
12. If so, list medications taken.______________________________
13. Do you have any respiratory problems (Example: asthma, emphysema)?
YES NO

14. If so, list them. ______________________________
15. Do you have any orthopedic problems (Example: arthritis, low back pain)?
YES NO

16. If so, list them. ______________________________
17. Have you had any recent illness, hospitalization, or surgical procedures?

YES NO
17. If so, list them and when?______________________________
18. Are you currently taking any medications? YES NO
19. If so, list them. ______________________________

20. Do you have any allergies? YES NO
21. If so, list them. ______________________________
22. Do you have any other conditions or problems that may affect your ability to

exercise? YES NO

23. If so, list them. ______________________________________________

Please provide us with emergency contact information.

Name: ___________________________ Home Phone: __________________

Relation: _________________________ Work Phone: __________________

# APPENDIX B

## HUMAN SUBJECTS REVIEW

## THE EFFECT OF A NEAR-MAXIMAL EFFORT ONE-HOUR RUN STRIDE RATE AND LEG FORCES

Iain Hunter, PhD student and Gerald A. Smith, PhD

### Brief Description

Alterations in distance running technique are often found as runners become fatigued. Preferred stride rate, the number of strides per second runners naturally choose, will be compared to optimal stride rate, the stride rate that uses the least amount of oxygen for any given speed, at the beginning and end of a one-hour, near maximal run. It is expected that preferred stride rate will decrease over the course of the run. Determining whether or not optimal stride rate decreases with preferred is the main question of interest. Leg stiffness, how "bouncy" the leg acts, will also be measured to check for any associations with stride rate. An association here may help explain why preferred stride rate is changing.

### Methods and Procedures

Subjects will perform two one-hour runs with one-week between each. Both runs will be performed on a treadmill instrumented to record vertical force. The first run will be used to determine an appropriate running pace, which will place the runner near exhaustion after one hour of steady running. This pace will be initially predicted based on a runner's competitive history if available (for example, 10 km race times) or on training history. Pace adjustments faster or slower will be made based on the subject's performance and perceptions in the first hour run.

The second run will be completed at a fixed speed, but stride rate will be manipulated using a computer-based metronome. At the five-minute mark, the runners will go though a stage of manipulated stride rates. Five different stride rates including, preferred and plus and minus four and eight percent of preferred. The runners will run for two minutes at each of these altered stride rates. Subjects will be told when the stride rate manipulation will occur and will know how far from their preferred it will be. At the 50-minute mark, the same manipulation of stride rates will occur, bringing us to the end of the run. During both runs, the subjects will be asked at least every fifteen minutes how they are feeling and if they need to stop. During the runs, subjects will be allowed to watch TV or listen to the radio.

During the stride rate manipulations, oxygen uptake will be recorded using a SensorMedics 2000 metabolic cart. This will require that the subject wear a nose clip and breathe room air though a mouthpiece so that the volume and concentration of exhaled air can be determined. The mouthpiece will not be required outside of the stride rate manipulations.

A max $\dot{V}O_2$ test will be required of each subject. The test will employ 1-

minute stages. Prior to the test, a 4-minute warm-up period will be given at a speed of 6 miles per hour (mph) and 0% grade. The first stage of the test will be conducted at the warm-up speed and grade (6 mph, 0% grade). Speed will be increased 0.5 mph per stage for stages two through seven, while treadmill elevation will remain at 0%. After completing the seventh stage (9 mph, 0% grade), no further speed increases will occur. However, treadmill grade will be increased 1% per stage until the subject becomes too exhausted to continue. Throughout the test, oxygen consumption will be measured over 20 second intervals using the same equipment as described above. Heart rate will be continuously recorded with a heart rate monitor. The test should take approximately 20 minutes with only the final few minutes being at a high intensity.

### Benefits and Risks

Subjects will receive a $10 stipend, description of their results, and refreshments for participation in the study.

Most endurance trained runners are capable of maintaining fairly difficult paces for one hour during racing or training and will find the testing of this project to be similar to races or hard training runs completed in the past. The stride rate manipulations of this study will carry some additional risk of falling. However, pilot collections have helped determine plus and minus eight percent limits for the manipulations as reasonable for maintaining stability on the treadmill.

Tests of maximal oxygen consumption have a very remote chance of precipitating a cardiac event (such as abnormal heart rhythms) or even death. However, the possibility of such an occurrence is very slight (less than 1 in 10,000), since participants will be in good physical condition with no known symptoms of heart disease. Furthermore, the test will be administered by trained personnel who will be monitoring for signs of exercise intolerance.

### Subject Population

Fifteen subjects will be recruited from the university population and local running clubs. Gender and race/ethnicity will not be restricted. All subjects will be over 18 years old. They must be currently training at least 20 miles per week for at least four weeks and be injury free. They must also have no history of heart disease.

### Informed Consent Process

Informed consent will be obtained from each subject prior to the first run (see attached consent form).

### Anonymity or Confidentiality

After completing the informed consent, subjects will be assigned a number. Only numbers will be used in analysis and presentation to preserve the anonymity and confidentiality of each subject.

## CONSENT FORM

**TITLE:** The Effect of a Near-Maximal Effort One-Hour Run on Preferred and Optimal Stride Rates

**INVESTIGATORS:** Iain Hunter, PhD student and Gerald A. Smith, PhD.

**PURPOSE:** Throughout a fatiguing run, the body goes through physiological changes. Specifically, the muscles of the leg react differently to activation signals. The changes in the leg may lead to alterations of preferred stride rate, the rate runners naturally select. Previous research has shown that in a rested condition, preferred stride rate matches the stride rate that minimizes oxygen uptake for any given speed, optimal stride rate. This study will investigate whether preferred stride rate matches optimal stride rate even when the preferred changes as the runner becomes fatigued.

**I HAVE RECEIVED AN ORAL EXPLANATION OF THE STUDY PRECEDURES AND UNDERSTAND THAT THEY ENTAIL THE FOLLOWING:**

All testing will be conducted in the biomechanics laboratory in the Women's Building at Oregon State University. As a subject, I will report to the laboratory three times for data collection. This will involve:

PRE-STUDY SCREENING: Researchers will check to see whether I have been training at least 20 miles per week and if I have any injuries or health concerns that would limit my ability to participate including a history of heart disease or running related overuse injuries. A health questionnaire will be used which may exclude me from participation.

ONE-HOUR RUNS: Height and weight will be measured. Two one-hour runs at near maximal effort on a treadmill will be required. The runs will take place at least one week apart. The pace of each run will be predetermined by estimated performance (based upon current 10 km race performance) or if I am unsure of my current performance ability, I will make my best guess at how fast I can run for an hour and the researchers will adjust the speed if necessary.

The second run will be completed close to the pace of the first, but may be adjusted if I feel I can run faster or need to go slower. During two 10-minute stages of the second run, I will have to set my stride length to plus and minus 4 and 8% of my preferred stride length. This will be done by listening to a metronome that the researchers will control. During these two 10-minute stages of the study, oxygen uptake will be monitored. This will require that I wear a nose clip and breathe room air though a mouthpiece so that the volume and concentration of my exhaled air can be determined. During the run, I will be allowed to listen to a radio or watch videos.

MAXIMUM OXYGEN CAPACITY (MAX $\dot{V}O_2$) TEST: At least three days after completing the final one-hour run, a maximum oxygen capacity (max $\dot{V}O_2$) test will be performed. This will measure the maximum amount of oxygen I am capable of consuming per minute. This test will employ 1-minute stages. Prior to the test, a 4-minute warm-up period will be given at a speed of 6 miles per hour (mph) and 0% grade. The first stage of the test will be conducted at the warm-up speed and grade (6 mph, 0% grade). Speed will be increased 0.5 mph per stage for stages two through seven, while treadmill elevation will remain at 0%. After completing the seventh stage (9 mph, 0% grade), no further speed increases will occur. However, treadmill grade will be increased 1% per stage until I become too exhausted to continue. Oxygen uptake will be measured throughout this test. The same equipment as described above will be used to measure oxygen uptake. My heart rate will be continuously recorded using a heart rate monitor. The test should take approximately 20 minutes with only the final few minutes being at a high intensity.

ASSOCIATED RISKS: I understand that the test of maximal oxygen consumption has a very remote chance of precipitating a cardiac event (such as abnormal heart rhythms) or even death. However, because I am in good physical condition with no known symptoms of heart disease the possibility of such an occurrence is very slight (less than 1 in 10,000). Furthermore, the test will be administered by trained personnel who will be monitoring for signs of exercise intolerance.

In addition to the risks stated above, stride rate and length will be manipulated 4 and 8% above and below preferred rate and length, adding to the risk of falling. To help decrease this risk, I will be informed when these changes will occur.

BENEFITS TO BE EXPECTED FROM THE RESEARCH: Participation in this study will contribute to the scientific study of running technique. I will receive $10, a description of my results and refreshments for participation in the study.

**CONFIDENTIALITY:** After completing the informed consent, subjects will be assigned a number. Only numbers will be used in analysis and presentation to preserve the anonymity and confidentiality of each subject.

**COMPENSATION FOR INJURY:** I understand that the University does not provide a research subject with compensation or medical treatment in the event that the subject is injured as a result of participation in the research project.

**VOLUNTARY PARTICIPATION STATEMENT:** I affirm that my participation in this study is completely voluntary. I understand that I may either refuse to participate or withdraw from the study at any time without penalty or loss of benefits to which I am otherwise entitled. I understand that if I withdraw from the study before it is completed, the amount of money or other compensation that I receive for participating may be less than the full amount.

**IF YOU HAVE QUESTIONS:** I understand that any questions I have about the research study or specific procedures should be directed to:
Iain Hunter
hunteri@ucs.orst.edu
(541)753-5180

If I have questions about my rights as a research subject, I should contact the IRB Coordinator, OSU Research Office, (541)737-3437.

**My signature below indicates that I have read and that I understand the procedures described above and give my informed and voluntary consent to participate in this study. I understand that I will receive a signed copy of this consent form.**

| | |
|---|---|
| Signature of subject (or subject's legally authorized representative) | Date Signed |
| Subject's Name (Printed) | |
| Subject's Present Address | Subject's Telephone Number |
| Signature of Principal Investigator | Date Signed |

Report of Review by the Institutional Review Board for the
Protection of Human Subjects
February 16, 2001

TO: Gerald Smith
Exercise and Sport Science

COPY: Laura Lincoln

RE: The Effect of a Near-Maximal Effort One-Hour Run on Preferred and Optimal Stride Rates

The referenced project was reviewed under the guidelines of Oregon State University's institutional review board (IRB), the Committee for the Protection of Human Subjects, and the U.S. Department of Health and Human Services. The IRB has approved your application. The approval of this application expires upon the completion of the project or one year from the approval date, whichever is sooner. The informed consent form obtained from each subject should be retained in program/project's files for three years beyond the end date of the project.

Any proposed change to the protocol or informed consent form that is not included in the approved application must be submitted to the IRB for review and must be approved by the committee before it can be implemented. Immediate action may be taken where necessary to eliminate apparent hazards to subjects, but this modification to the approved project must be reported immediately to the IRB.

# APPENDIX C

# LITERATURE REVIEW

## Stride Rate and Running Economy

Many studies show high correlations between max $\dot{V}O_2$ and distance racing performance (Costill, 1967, Costill, 1973, Farrell, 1979, Foster, 1978). The typical high correlations between max $\dot{V}O_2$ and racing performance demonstrate the importance of $\dot{V}O_2$ in distance running. When subjects were limited to elite runners who all have a high max $\dot{V}O_2$, some studies showed relatively low correlations between max $\dot{V}O_2$ and performance (Morgan, 1989). Running economy, the amount of oxygen uptake at a given workload, has a linear relationship with running velocity (Conley, 1980). Using technique that modifies this relationship may allow runners to maintain given speeds for a longer time (Figure C.1). Previous research shows non-fatigued runners naturally choose a stride rate that minimizes oxygen use (Cavanagh, 1982). This paper will refer to the stride rate that minimizes oxygen cost at a given speed as optimal or most economical stride rate.

Cavanagh and Williams determined optimal stride rate by recording oxygen uptake through a range of stride rates 20% below to 20% above a runner's preferred rate. The minimum value of a quadratic fit placed through these data matches up with optimal stride rate (Figure C.2). Their results showed no significant differences between preferred and optimal stride rates. Thus, in a non-

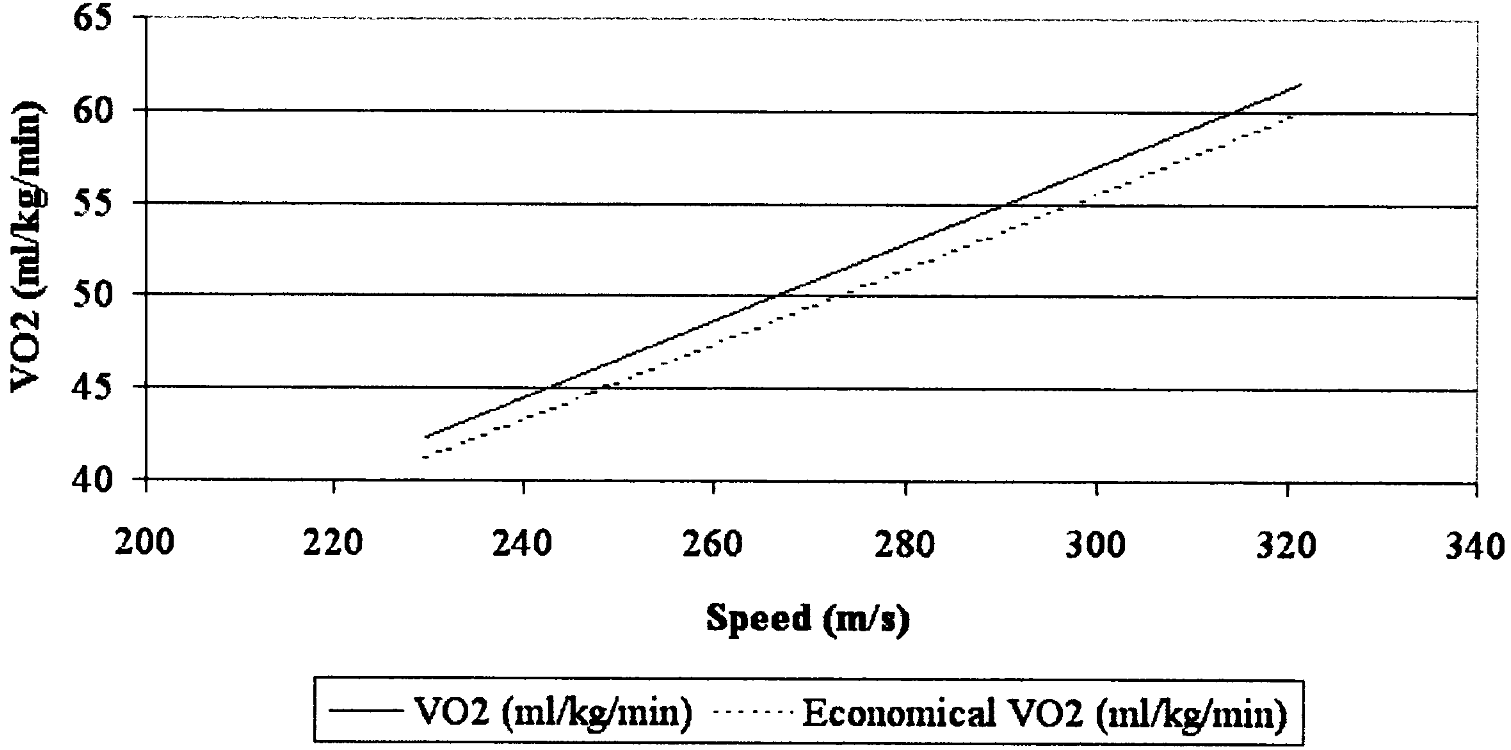

Figure C.1
Benefit of economical running. Higher speeds can be sustained at similar oxygen uptakes. Regression equation used to create chart taken from Conley (1980). Economical $\dot{V}O_2$ line is theoretical.

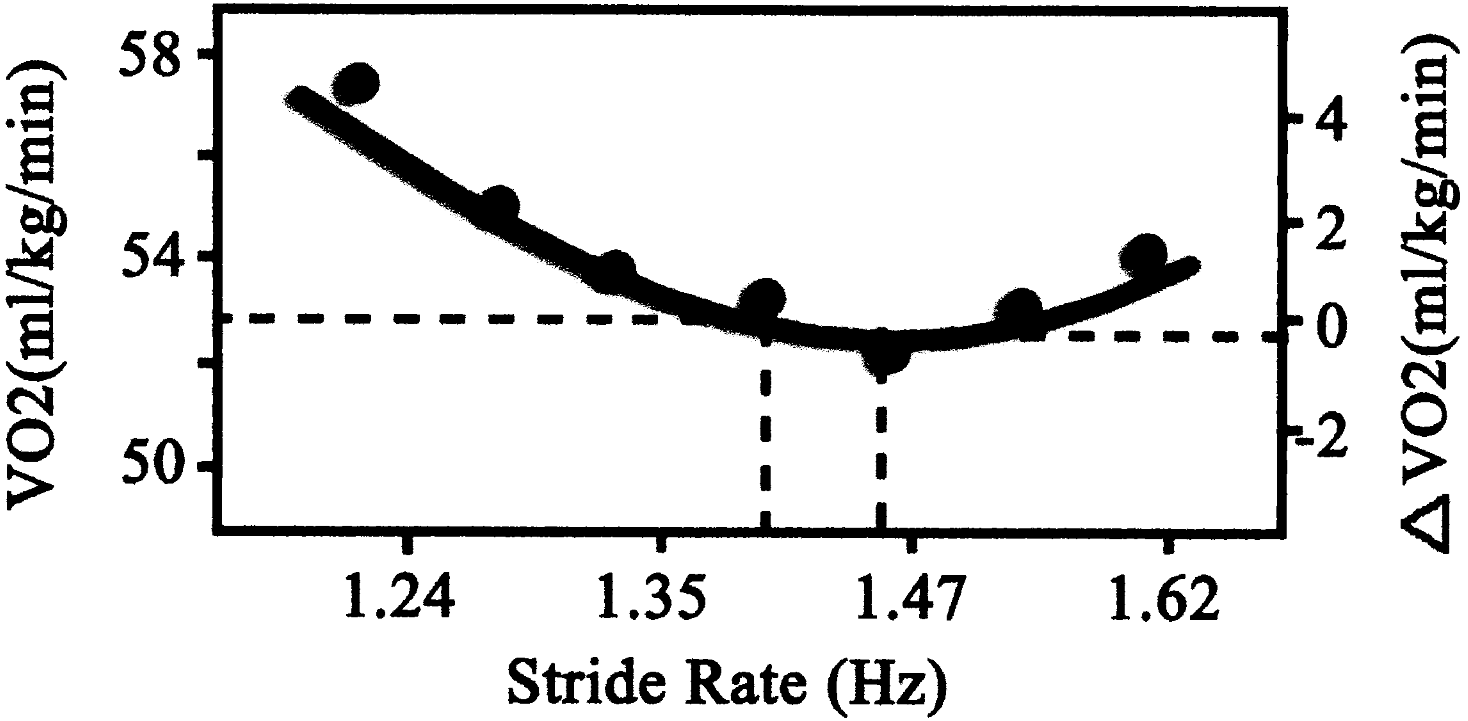

Figure C.2
Preferred and optimal stride rate (modified from Cavanagh and Williams, 1981).

fatigued state, experienced runners freely choose the optimal stride rate for the speed they are running.

## Stride Rate and Fatigue

Candau et al. showed a significant decrease in stride rate during a treadmill run to exhaustion (1998). Their study is very applicable here since running speed was held constant as will ours. In studies where speed was not held constant, decreases in stride rate were due more to decreases in speed than increases in fatigue. However, Williams et al. found decreases in stride rate even after using regression to account for speed changes (1988).

In a 3000 m time trial, runners increased stride rate according to Elliot and Roberts (1980). Speed was held constant in this time trial. This limits the study since runners were not likely near exhaustion because the predicted speed was probably not quite at their maximal speed for a 3000 m run. Also, this race is relatively short so the body is not in the same condition as it would have been in a longer run to exhaustion.

Alterations in stride rate do not always occur when runners become fatigued. Elliot and Ackland found runners in a 10,000 m race maintain stride rate throughout the run (1981). Some studies show no significant differences in stride rate with fatigue because some subjects showed increases and others showed decreases averaging close to zero (Nicol, 1991).

Pilot data collected by myself of two subjects showed a decrease in stride rate for both runners near the end of approximately one-hour long runs. It is clear that changes in stride rate due to fatigue often occur, but no consistent patterns seem to exist between individuals. However, most of the studies leaned towards a decrease in stride rate, especially when speed was held constant and the time of the run was thirty or more minutes.

## Physiological Changes with Fatigue

While many changes occur in the body with extended exercise, fatigue during a near maximal one-hour run is the focus in this study. Depending upon the mode and intensity, a variety of limiting factors could lead to voluntary or involuntary termination of exercise. During a near maximal one-hour run, hydrogen ions ($H^+$) are released from lactic acid and inorganic phosphate ($P_i$) is released in the degradation of ATP. The increases in $H^+$ lead to decreases in pH may limit performance in this type of run. Phosphofructokinase is inhibited by $H^+$, which leads to decreases in glycolytic capacity and disassociation of calcium ions from troponin, interfering with muscle contraction. If the run is sufficiently above lactate threshold, increases in $P_i$ will bind to calcium in the sarcoplasmic reticulum, decreasing force at the crossbridge. Finally, the decreased pH may result in pain (Brooks, p. 804-806, 2000). Fatigue is a very complex issue, but for a one-hour near maximal run, as will be used in this study, the increased $H^+$and $P_i$ and decreased pH are likely the main factors leading to exhaustion.

The changes occurring on the cellular level help explain alterations in muscle capacities. Running involves concentric, eccentric, and isometric muscle activity. A reduction in isometric peak force occurs when muscles become fatigued (De Haan, 1989). Hamstring peak torque creation is decreased in fatigued muscle (Pinniger, 2000). When muscles become fatigued, maximum shortening velocity is reduced (De Haan, 1989). While the muscles are probably not required to reach peak isometric force or maximum shortening velocity in running, these muscular limitations are evidence of physical changes which may lead to altered technique.

Motor unit firing frequency is linearly related to motor unit force. This force-frequency relationship suggests that muscle can create greater force with increased activation frequency. As muscles become fatigued, there is a change in the force-frequency relationship. In a fatigued state, activation frequency must be increased to maintain force production (Binder-Macleod, 1998).

EMG duration increases as runners become fatigued, starting earlier and finishing later around the stance phase (Pinniger, 2000). Slight technique changes were associated with the increases in EMG duration in Pinniger's study, including a decrease in stride rate.

Pinniger also found significant decreases in hamstring peak torque creation in fatigued muscle (2000). While running does not require a person to create peak torques, the muscle is obviously in a different state if its performance level is altered.

Tendons and bones may suffer microdamage during extended repetitious exercise. As tissues become damaged due to repetitious exercise, it seems likely that locomotion may undergo altered technique to minimize further damage, which may affect movement economy. Changes in stride rates may take place to decrease impact frequency or peak force.

### Fatigue and Vertical Stiffness

Speed, stride rate, running surface, and cost of running have all been associated with vertical stiffness. Speed and stride rate often change with fatigue, so changes in vertical stiffness are also expected. However, limited research has been performed to associate fatigue with stiffness parameters.

Dutto found leg stiffness to change in 14 out of 15 subjects through fatigue-induced changes in stride rate (2000). However, the trends were not consistent between subjects. Most showed decreases in stiffness, while some showed small increases. As muscular changes occur the elastic properties of muscle may change. This could create a change in leg stiffness, perhaps leading to altered technique. A lack of research leaves the possible association between fatigue and leg stiffness unclear.

### Optimal Stride Rate while Fatigued

The fatigue-induced physiological changes described above may explain alterations in technique. It is clear that some aspects of technique may change as runners become fatigued. Physiological changes in the body due to fatigue probably cause these technique modifications. In non-fatigued distance runners, Cavanagh and Williams determined that athletes or coaches should not consciously manipulate stride rate as oxygen uptake would increase (1982). The body of a fatigued runner is in a different state than a non-fatigued runner. Since the state of the body is changed, it follows that optimal stride rate could change also.

## Background and significance

Distance running is one of the most popular competitive sports in the world. This Olympic year brought excitement over the sport among recreational and competitive runners alike. As athletes prepare for competition, they focus on endurance, strength, and technique. Technique improvements help athletes move faster and more economically.

One aspect of technique that is easy to manipulate is stride rate. Coaches often give cues telling athletes to increase or decrease their stride rate especially near the end of a race. Cavanagh and Williams report that at distance running speeds, in a non-fatigued state, experienced runners have the ability to select a stride rate that economizes running technique (1982). "Most economical" running will be used here to mean technique that minimizes oxygen use. The stride rate runners naturally select, preferred stride rate, varies from person to person and seems to be independent of height, weight, leg-length, other anthropometric variables, and changes only slightly throughout distance running speeds, but tends to match the most economical or optimal stride rate (Cavanagh & Kram, 1989).

Other research shows possible changes in stride rate as runners become fatigued. Candau et al. (1998) report a 0.09 (SD 0.05) % decrease in preferred stride rate during a run to exhaustion at 3000 m personal record speed. In contrast, Elliot and Ackland found no change in stride rate during a 10,000 m run (1981). Elliott and Roberts observed an increase in stride rate at the very end of a 3000 m time trial held at a constant speed (1980). These three studies have varying results reporting decreases, no change, and increases in stride rate with fatigue. Such contradictory results may be due in part to different methodologies. If the runner's pace was not controlled with a treadmill, stride rate changes may have been due to speed changes. However, when treadmill speed was held constant or regression equations accounted for the differences in speed, a variety of results were still found (Williams, 1988). In general, most studies report that runners change their preferred stride rate as they become fatigued.

Considering the ability of runners to find the most economical stride rate in a non-fatigued state and the fact that a stride rate may change with fatigue creates an interesting question which is the main focus of this study: If preferred stride rate changes with fatigue, does optimal stride rate change as well?

Physiological changes occur in the body as one becomes fatigued. Included in these changes are a decreased maximum shortening velocity and peak power of muscle, a decreased activation frequency, and a need for more muscle fiber recruitment to maintain muscle force. These physical changes likely cause alterations in running technique. It is possible that when changes in stride rate occur with fatigue, the body is adjusting its running pattern to keep the most economical stride rate for the situation.

While some research demonstrates a change in stride rate with fatigue, the reasons for these rate changes are unclear. Vertical stiffness may help explain part of the variability associated with stride rate changes. As a runner goes through the stance phase of a stride, eccentric and concentric muscle activity occurs. Energy is stored in muscle and tendon during the eccentric phase, then released during the concentric phase (Dalleau, 1998). This is often illustrated using a mass-spring model (Figure C.3). This model describes the body's center of mass as following a downward arc throughout the stance phase. During this phase, the leg and other parts of the body are compressed representing the spring in the model. Stiffness constants for this spring are calculated by dividing the maximum force by the displacement at the time of maximum force during the stance phase.

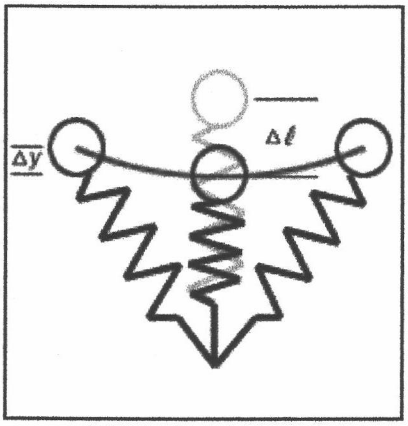

Figure C.3
Mass-spring model of the body in running (Adapted from McMahon, 1990).

Two stiffness constants are typically calculated to describe the spring characteristics of the leg when discussing locomotion. One is vertical stiffness, which is described by the peak force divided by the center of mass vertical change of position from the beginning of stance to the time of peak force ($\Delta y$ of Figure C.3). The other constant commonly calculated is leg stiffness described as peak force divided by leg shortening at the time of peak force ($\Delta l$ of Figure C.3).

Figure C.4 demonstrates a limitation of using the mass-spring model. After calculating modeled ground reaction forces (GRF) based upon the vertical stiffness parameter, modeled and real GRF were plotted together. Distortions are easy to see in shape and stance time when using this model. Although reproduction of real GRF is not very accurate, vertical stiffness can still be useful in predicting kinetic and potential energy changes and give the basic shape of the GRF during stance. Vertical stiffness, calculated from a simple mass-spring model, is also associated with speed, stride rate, and surface stiffness.

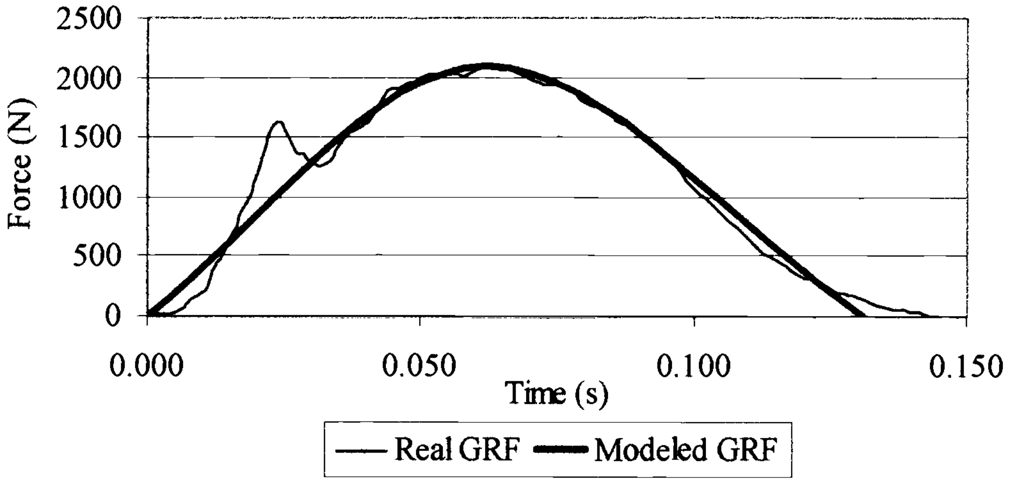

Figure C.4-Comparing real with modeled ground reaction force curves based upon the simple mass-spring model (taken from pilot data).

Derrick et al. (2000) created a modified mass-spring-damper model that describes the action of the body during stance phase much better than the simple mass-spring model. It involves two masses, two springs, and a damper, as shown in Figure C.5. The division is not exactly clear, but is described with the upper mass, $M_1$, represents the upper body and the swing leg, while the lower mass, $M_2$, represents the support leg. Twenty percent of the total body mass is attributed to $M_2$. Although this is an overestimate according to typical values (for example, approximately 16%, Zatsiorsky, p. 272-291, 1990), the authors found the model to be most accurate using this division.

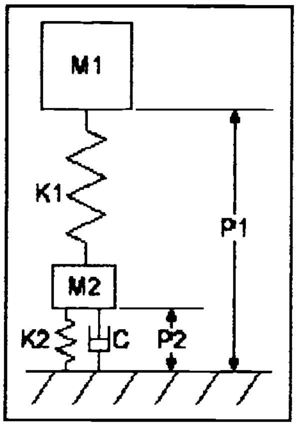

Figure C.5-Mass-spring/Mass-spring-damper model of the body in running.

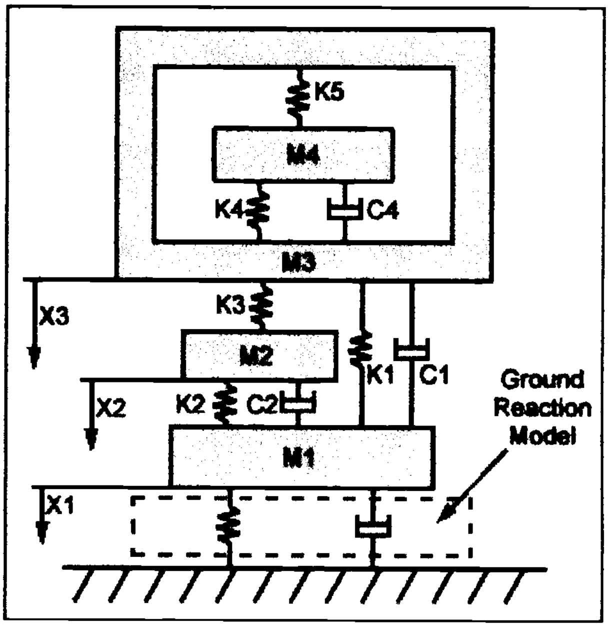

Figure C.6-Complex model of the body in running (Nigg, 1999).

The parameters found using these various models can be correlated with changes in stride rate. Farley and Gonzalez found the leg spring becomes stiffer as stride frequency increases (1996). Derrick's model showed changes in the stiffness of the upper spring while modeling various stride rates. These correlations are encouraging in the present study since stride rate is expected to change near the end of the run.

One last model worth mentioning here was presented by Nigg (Figure C.6, 1999). Each part of the body is represented by wobbling and rigid components. Although the exact division is unclear, the upper masses represent the upper body and swing leg, while the lower masses represent the stance leg. The springs and dampers were attached as shown in Figure C.6. The combination of $k_1$, $k_2$, & $k_3$ describe the leg stiffness used in the simple mass-spring model. Along with the difficulty that exists in computing this model, interpreting what each component of the model represents is complicated.

Which model is best? This depends upon the goal of research. When using these models to reproduce original force-time curves, Nigg's model may be the most accurate due to its complexity. It seems that as more components are added to models, more variance is explained. However, interpreting changes from certain parameters is very complex since there are no clear definitions of what each mass spring and damper really represents. On the other hand, while very simple, the mass-spring model can reproduce the force-time curve reasonably well other than the impact peak. Visualizing the mass-spring model is fairly simple and only leg and vertical stiffness need to be considered. This makes it desirable for analyses that do not require detailed descriptions of motion. If the research is able to find information from this model, it serves its purpose well.

# APPENDIX D
# SUBJECT DATA

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.364 | 53.7 | 32.3 | 1.241 | 51.6 | 33.3 |
| 1.419 | 52.4 | 33.7 | 1.295 | 49.3 | 34.8 |
| 1.470 | 50.9 | 34.9 | 1.349 | 48.3 | 35.1 |
| 1.538 | 52.5 | 36.6 | 1.403 | 51.1 | 36.5 |
| 1.596 | 53.8 | 38.8 | 1.473 | 50.4 | 39.3 |

Table D.1
Subject 1 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.479 |
| 33% | 1.450 |
| 42% | 1.458 |
| 50% | 1.450 |
| 58% | 1.452 |
| 67% | 1.444 |
| 75% | 1.408 |
| 83% | 1.359 |

Table D.2
Subject 1 stride rate profile

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 24.4 | 34.9 | 0.340 | 0.338 |
| 2 | 29.2 | 26.6 | 0.336 | 0.336 |
| 3 | 26.5 | 26.3 | 0.347 | 0.341 |
| 4 | 28.3 | 26.1 | 0.345 | 0.341 |
| 5 | 26.8 | 25.6 | 0.341 | 0.342 |
| 6 | 25.3 | 27.2 | 0.342 | 0.345 |
| 7 | 27.1 | 26.7 | 0.341 | 0.340 |
| 8 | 26.6 | 25.8 | 0.343 | 0.343 |
| 9 | 25.2 | 25.6 | 0.339 | 0.344 |
| 10 | 25.7 | 26.5 | 0.342 | 0.338 |
| 11 | | | 0.340 | 0.342 |
| 12 | | | 0.340 | 0.341 |
| 13 | | | 0.342 | 0.343 |
| 14 | | | 0.342 | 0.338 |
| 15 | | | 0.345 | 0.338 |
| 16 | | | 0.340 | 0.342 |
| 17 | | | 0.352 | 0.342 |
| 18 | | | 0.342 | 0.343 |
| 19 | | | 0.342 | 0.341 |
| 20 | | | 0.341 | 0.340 |
| 21 | | | 0.345 | 0.342 |
| 22 | | | 0.340 | 0.344 |
| 23 | | | 0.340 | 0.342 |
| 24 | | | 0.335 | 0.339 |
| 25 | | | 0.339 | 0.340 |
| 26 | | | 0.339 | 0.342 |
| 27 | | | 0.338 | 0.343 |
| 28 | | | 0.340 | 0.341 |
| 29 | | | 0.338 | 0.348 |
| 30 | | | 0.339 | 0.336 |
| 31 | | | 0.346 | 0.338 |
| 32 | | | 0.343 | 0.338 |
| 33 | | | 0.339 | 0.344 |
| 34 | | | 0.340 | 0.342 |
| 35 | | | 0.342 | 0.339 |
| 36 | | | 0.336 | 0.336 |
| 37 | | | 0.339 | 0.343 |
| 38 | | | 0.341 | 0.342 |
| 39 | | | 0.340 | 0.335 |
| 40 | | | 0.340 | 0.336 |
| 41 | | | 0.340 | 0.337 |
| 42 | | | 0.338 | 0.342 |
| 43 | | | 0.333 | 0.338 |
| Avg | 26.5 | 27.1 | 0.341 | 0.340 |
| SD | 1.5 | 2.8 | 0.003 | 0.003 |

Table D.3
Subject 1 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.297 | 49.6 | 30.7 | 1.291 | 51.3 | 32.1 |
| 1.349 | 49.7 | 35.9 | 1.349 | 50.3 | 34.9 |
| 1.389 | 48.1 | 38.0 | 1.398 | 48.0 | 34.8 |
| 1.474 | 49.7 | 41.0 | 1.405 | 49.3 | 36.5 |
| 1.481 | 49.7 | 45.0 | 1.425 | 50.1 | 38.8 |

Table D.4
Subject 2 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.416 |
| 33% | 1.419 |
| 42% | 1.422 |
| 50% | 1.424 |
| 58% | 1.408 |
| 67% | 1.389 |
| 75% | 1.395 |
| 83% | 1.402 |

Table D.5
Subject 2 stride rate profile

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 26.8 | 29.3 | 0.361 | 0.359 |
| 2 | 29.4 | 28.7 | 0.355 | 0.359 |
| 3 | 27.9 | 29.1 | 0.366 | 0.356 |
| 4 | 29.9 | 28.5 | 0.357 | 0.359 |
| 5 | 27.1 | 29.0 | 0.358 | 0.359 |
| 6 | 28.7 | 29.0 | 0.360 | 0.361 |
| 7 | 27.4 | 30.6 | 0.360 | 0.357 |
| 8 | 33.0 | 30.2 | 0.360 | 0.360 |
| 9 | 28.6 | 29.3 | 0.362 | 0.359 |
| 10 | 30.4 | 28.4 | 0.364 | 0.357 |
| 11 | | | 0.363 | 0.359 |
| 12 | | | 0.360 | 0.358 |
| 13 | | | 0.365 | 0.354 |
| 14 | | | 0.362 | 0.356 |
| 15 | | | 0.366 | 0.358 |
| 16 | | | 0.361 | 0.358 |
| 17 | | | 0.359 | 0.356 |
| 18 | | | 0.357 | 0.357 |
| 19 | | | 0.362 | 0.354 |
| 20 | | | 0.361 | 0.356 |
| 21 | | | 0.361 | 0.356 |
| 22 | | | 0.361 | 0.356 |
| 23 | | | 0.363 | 0.356 |
| 24 | | | 0.355 | 0.356 |
| 25 | | | 0.356 | 0.356 |
| 26 | | | 0.357 | 0.359 |
| 27 | | | 0.358 | 0.353 |
| 28 | | | 0.354 | 0.362 |
| 29 | | | 0.360 | 0.354 |
| 30 | | | 0.359 | 0.361 |
| 31 | | | 0.359 | 0.356 |
| 32 | | | 0.359 | 0.360 |
| 33 | | | 0.359 | 0.359 |
| 34 | | | 0.362 | 0.357 |
| 35 | | | 0.364 | 0.356 |
| 36 | | | 0.357 | 0.357 |
| 37 | | | 0.363 | 0.358 |
| 38 | | | 0.359 | 0.357 |
| 39 | | | 0.357 | 0.357 |
| 40 | | | 0.359 | 0.358 |
| Avg | 28.9 | 29.2 | 0.360 | 0.357 |
| SD | 1.9 | 0.7 | 0.003 | 0.002 |

Table D.6
Subject 2 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.291 | 53.1 | 40.5 | 1.256 | 54.3 | 37.1 |
| 1.349 | 49.3 | 41.6 | 1.310 | 53.3 | 39.8 |
| 1.405 | 48.9 | 42.2 | 1.352 | 49.8 | 43.0 |
| 1.461 | 50.6 | 45.3 | 1.421 | 52.5 | 44.3 |
| 1.515 | 52.5 | 47.6 | 1.470 | 54.9 | 50.4 |

Table D.7
Subject 3 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.405 |
| 33% | 1.412 |
| 42% | 1.403 |
| 50% | 1.400 |
| 58% | 1.401 |
| 67% | 1.377 |
| 75% | 1.377 |
| 83% | 1.365 |

Table D.8
Subject 3 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 29.8 | 30.9 | 0.355 | 0.357 |
| 2 | 27.7 | 33.6 | 0.355 | 0.358 |
| 3 | 28.6 | 27.3 | 0.353 | 0.360 |
| 4 | 27.3 | 28.5 | 0.354 | 0.374 |
| 5 | 28.7 | 29.8 | 0.354 | 0.365 |
| 6 | 28.9 | 29.0 | 0.360 | 0.369 |
| 7 | 27.1 | 27.1 | 0.365 | 0.368 |
| 8 | 30.3 | 29.7 | 0.355 | 0.373 |
| 9 | 27.6 | 28.7 | 0.350 | 0.374 |
| 10 | 28.1 | 29.6 | 0.365 | 0.375 |
| 11 | | | 0.360 | 0.371 |
| 12 | | | 0.365 | 0.369 |
| 13 | | | 0.367 | 0.367 |
| 14 | | | 0.355 | 0.367 |
| 15 | | | 0.355 | 0.370 |
| 16 | | | 0.355 | 0.364 |
| 17 | | | 0.353 | 0.367 |
| 18 | | | 0.354 | 0.362 |
| 19 | | | 0.360 | 0.370 |
| 20 | | | 0.365 | 0.375 |
| 21 | | | 0.355 | 0.367 |
| 22 | | | 0.350 | 0.371 |
| 23 | | | 0.365 | 0.370 |
| 24 | | | 0.360 | 0.371 |
| 25 | | | 0.365 | 0.371 |
| 26 | | | 0.366 | 0.370 |
| 27 | | | 0.355 | 0.372 |
| 28 | | | 0.355 | 0.372 |
| 29 | | | 0.355 | 0.371 |
| 30 | | | 0.353 | 0.373 |
| 31 | | | 0.354 | 0.376 |
| 32 | | | 0.360 | 0.371 |
| 33 | | | 0.365 | 0.371 |
| 34 | | | 0.355 | 0.368 |
| 35 | | | 0.350 | 0.371 |
| 36 | | | 0.365 | 0.383 |
| 37 | | | 0.360 | 0.373 |
| 38 | | | 0.365 | 0.371 |
| 39 | | | 0.367 | 0.373 |
| 40 | | | 0.355 | 0.381 |
| Avg | 28.4 | 29.4 | 0.358 | 0.370 |
| SD | 1.1 | 1.9 | 0.005 | 0.005 |

Table D.9
Subject 3 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.398 | 38.2 | 22.4 | 1.415 | 39.5 | 24.0 |
| 1.459 | 39.0 | 24.8 | 1.475 | 39.6 | 25.1 |
| 1.513 | 36.0 | 25.0 | 1.501 | 37.7 | 26.2 |
| 1.527 | 37.8 | 25.0 | 1.539 | 39.5 | 26.8 |
| 1.636 | 39.7 | 29.8 | 1.597 | 40.0 | 26.6 |

Table D.10
Subject 4 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.520 |
| 33% | 1.526 |
| 42% | 1.526 |
| 50% | 1.520 |
| 58% | 1.520 |
| 67% | 1.534 |
| 75% | 1.514 |
| 83% | 1.481 |

Table D.11
Subject 4 stride rate profile

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 22.1 | 20.4 | 0.326 | 0.324 |
| 2 | 20.7 | 20.5 | 0.322 | 0.324 |
| 3 | 20.9 | 20.1 | 0.329 | 0.322 |
| 4 | 20.4 | 19.5 | 0.327 | 0.324 |
| 5 | 21.2 | 20.5 | 0.327 | 0.324 |
| 6 | 20.1 | 19.6 | 0.323 | 0.326 |
| 7 | 20.7 | 20.7 | 0.332 | 0.324 |
| 8 | 19.6 | 20.9 | 0.328 | 0.323 |
| 9 | 21.6 | 20.0 | 0.329 | 0.322 |
| 10 | 19.7 | 20.8 | 0.326 | 0.325 |
| 11 | | | 0.332 | 0.325 |
| 12 | | | 0.323 | 0.325 |
| 13 | | | 0.327 | 0.323 |
| 14 | | | 0.325 | 0.323 |
| 15 | | | 0.329 | 0.326 |
| 16 | | | 0.327 | 0.324 |
| 17 | | | 0.326 | 0.324 |
| 18 | | | 0.330 | 0.325 |
| 19 | | | 0.326 | 0.327 |
| 20 | | | 0.331 | 0.325 |
| 21 | | | 0.323 | 0.326 |
| 22 | | | 0.328 | 0.325 |
| 23 | | | 0.331 | 0.325 |
| 24 | | | 0.326 | 0.325 |
| 25 | | | 0.329 | 0.320 |
| 26 | | | 0.329 | 0.324 |
| 27 | | | 0.329 | 0.323 |
| 28 | | | 0.327 | 0.323 |
| 29 | | | 0.325 | 0.320 |
| 30 | | | 0.330 | 0.324 |
| 31 | | | 0.327 | 0.325 |
| 32 | | | 0.328 | 0.326 |
| 33 | | | 0.328 | 0.323 |
| 34 | | | 0.327 | 0.324 |
| 35 | | | 0.328 | 0.321 |
| 36 | | | 0.330 | 0.325 |
| 37 | | | 0.325 | 0.326 |
| 38 | | | 0.326 | 0.320 |
| 39 | | | 0.329 | 0.323 |
| 40 | | | 0.329 | 0.325 |
| 41 | | | 0.330 | 0.326 |
| 42 | | | 0.333 | 0.321 |
| 43 | | | 0.333 | 0.320 |
| 44 | | | 0.332 | 0.322 |
| Avg | 20.7 | 20.3 | 0.328 | 0.324 |
| SD | 0.8 | 0.5 | 0.003 | 0.002 |

Table D.12
Subject 4 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.486 | 47.1 | 29.8 | 1.525 | 46.1 | 28.7 |
| 1.532 | 46.5 | 30.5 | 1.534 | 46.8 | 29.7 |
| 1.573 | 44.1 | 32.8 | 1.570 | 45.0 | 31.6 |
| 1.616 | 45.7 | 34.7 | 1.559 | 46.3 | 30.6 |
| 1.642 | 47.1 | 35.8 | 1.610 | 47.1 | 33.5 |

Table D.13
Subject 5 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.579 |
| 33% | 1.546 |
| 42% | 1.570 |
| 50% | 1.558 |
| 58% | 1.570 |
| 67% | 1.570 |
| 75% | 1.579 |
| 83% | 1.570 |

Table D.14
Subject 5 stride rate profile

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 24.4 | 24.4 | 0.320 | 0.321 |
| 2 | 26.1 | 26.4 | 0.318 | 0.318 |
| 3 | 27.1 | 27.3 | 0.319 | 0.319 |
| 4 | 25.0 | 24.3 | 0.321 | 0.321 |
| 5 | 25.1 | 27.2 | 0.319 | 0.318 |
| 6 | 26.3 | 25.8 | 0.319 | 0.323 |
| 7 | 26.5 | 24.2 | 0.322 | 0.320 |
| 8 | 24.8 | 25.1 | 0.319 | 0.319 |
| 9 | 26.9 | 27.5 | 0.318 | 0.318 |
| 10 | 26.0 | 25.5 | 0.314 | 0.313 |
| 11 | | | 0.321 | 0.322 |
| 12 | | | 0.318 | 0.318 |
| 13 | | | 0.313 | 0.315 |
| 14 | | | 0.321 | 0.320 |
| 15 | | | 0.319 | 0.318 |
| 16 | | | 0.316 | 0.317 |
| 17 | | | 0.318 | 0.317 |
| 18 | | | 0.320 | 0.322 |
| 19 | | | 0.319 | 0.319 |
| 20 | | | 0.317 | 0.316 |
| 21 | | | 0.315 | 0.316 |
| 22 | | | 0.314 | 0.313 |
| 23 | | | 0.314 | 0.314 |
| 24 | | | 0.314 | 0.317 |
| 25 | | | 0.317 | 0.316 |
| 26 | | | 0.317 | 0.318 |
| 27 | | | 0.319 | 0.317 |
| 28 | | | 0.318 | 0.317 |
| 29 | | | 0.319 | 0.315 |
| 30 | | | 0.317 | 0.319 |
| 31 | | | 0.317 | 0.320 |
| 32 | | | 0.317 | 0.319 |
| 33 | | | 0.320 | 0.316 |
| 34 | | | 0.318 | 0.321 |
| 35 | | | 0.318 | 0.320 |
| 36 | | | 0.319 | 0.312 |
| 37 | | | 0.315 | 0.318 |
| 38 | | | 0.314 | 0.313 |
| 39 | | | 0.318 | 0.320 |
| 40 | | | 0.318 | 0.318 |
| 41 | | | 0.318 | 0.318 |
| 42 | | | 0.316 | 0.315 |
| 43 | | | 0.316 | 0.320 |
| 44 | | | 0.318 | 0.318 |
| 45 | | | 0.318 | 0.316 |
| 46 | | | 0.318 | 0.320 |
| Avg | 25.8 | 25.8 | 0.318 | 0.318 |
| SD | 0.9 | 1.3 | 0.002 | 0.003 |

Table D.15
Subject 5 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.313 | 48.9 | 31.4 | 1.256 | 50.4 | 29.1 |
| 1.365 | 45.6 | 36.1 | 1.306 | 50.2 | 34.1 |
| 1.410 | 42.3 | 35.9 | 1.362 | 49.9 | 34.2 |
| 1.484 | 45.4 | 43.1 | 1.417 | 50.1 | 40.7 |
| 1.540 | 50.3 | 45.3 | 1.470 | 50.2 | 44.2 |

Table D.16
Subject 6 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.429 |
| 33% | 1.355 |
| 42% | 1.355 |
| 50% | 1.353 |
| 58% | 1.344 |
| 67% | 1.350 |
| 75% | 1.364 |
| 83% | 1.362 |

Table D.17
Subject 6 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 26.8 | 26.0 | 0.320 | 0.321 |
| 2 | 28.5 | 25.6 | 0.318 | 0.318 |
| 3 | 29.8 | 25.0 | 0.319 | 0.319 |
| 4 | 26.7 | 25.9 | 0.321 | 0.321 |
| 5 | 27.4 | 26.8 | 0.319 | 0.318 |
| 6 | 28.5 | 26.1 | 0.319 | 0.323 |
| 7 | 28.9 | 26.8 | 0.322 | 0.320 |
| 8 | 25.9 | 26.4 | 0.319 | 0.319 |
| 9 | 27.9 | 26.9 | 0.318 | 0.318 |
| 10 | 26.3 | 26.0 | 0.314 | 0.313 |
| 11 | | | 0.321 | 0.322 |
| 12 | | | 0.318 | 0.318 |
| 13 | | | 0.313 | 0.315 |
| 14 | | | 0.321 | 0.320 |
| 15 | | | 0.319 | 0.318 |
| 16 | | | 0.316 | 0.317 |
| 17 | | | 0.318 | 0.317 |
| 18 | | | 0.320 | 0.322 |
| 19 | | | 0.319 | 0.319 |
| 20 | | | 0.317 | 0.316 |
| 21 | | | 0.315 | 0.316 |
| 22 | | | 0.314 | 0.313 |
| 23 | | | 0.314 | 0.314 |
| 24 | | | 0.314 | 0.317 |
| 25 | | | 0.317 | 0.316 |
| 26 | | | 0.317 | 0.318 |
| 27 | | | 0.319 | 0.317 |
| 28 | | | 0.318 | 0.317 |
| 29 | | | 0.319 | 0.315 |
| 30 | | | 0.317 | 0.319 |
| 31 | | | 0.317 | 0.320 |
| 32 | | | 0.317 | 0.319 |
| 33 | | | 0.320 | 0.316 |
| 34 | | | 0.318 | 0.321 |
| 35 | | | 0.318 | 0.320 |
| 36 | | | 0.319 | 0.312 |
| 37 | | | 0.315 | 0.318 |
| 38 | | | 0.314 | 0.313 |
| 39 | | | 0.318 | 0.320 |
| 40 | | | 0.318 | 0.318 |
| 41 | | | 0.318 | 0.318 |
| 42 | | | 0.316 | 0.315 |
| 43 | | | 0.316 | 0.320 |
| 44 | | | 0.318 | 0.318 |
| 45 | | | 0.318 | 0.316 |
| 46 | | | 0.318 | 0.320 |
| Avg | 27.7 | 26.2 | 0.318 | 0.318 |
| SD | 1.3 | 0.6 | 0.002 | 0.003 |

Table D.18
Subject 6 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.299 | 60.1 | 34.5 | 1.309 | 60.0 | 36.4 |
| 1.353 | 59.9 | 37.3 | 1.421 | 57.8 | 39.2 |
| 1.412 | 57.8 | 41.2 | 1.425 | 57.2 | 40.0 |
| 1.465 | 59.5 | 42.9 | 1.478 | 59.0 | 42.2 |
| 1.523 | 60.8 | 46.9 | 1.541 | 59.8 | 45.7 |

Table D.19
Subject 7 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.442 |
| 33% | 1.434 |
| 42% | 1.442 |
| 50% | 1.424 |
| 58% | 1.424 |
| 67% | 1.414 |
| 75% | 1.414 |
| 83% | 1.407 |

Table D.20
Subject 7 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 28.6 | 27.0 | 0.354 | 0.357 |
| 2 | 30.9 | 29.8 | 0.358 | 0.351 |
| 3 | 29.0 | 29.0 | 0.349 | 0.350 |
| 4 | 31.7 | 31.2 | 0.355 | 0.355 |
| 5 | 30.2 | 28.4 | 0.354 | 0.350 |
| 6 | 33.1 | 32.5 | 0.354 | 0.353 |
| 7 | 27.9 | 27.7 | 0.354 | 0.347 |
| 8 | 33.5 | 32.7 | 0.354 | 0.346 |
| 9 | 27.0 | 30.1 | 0.347 | 0.346 |
| 10 | 33.7 | 32.0 | 0.350 | 0.355 |
| 11 | | | 0.350 | 0.350 |
| 12 | | | 0.361 | 0.356 |
| 13 | | | 0.352 | 0.350 |
| 14 | | | 0.354 | 0.354 |
| 15 | | | 0.350 | 0.352 |
| 16 | | | 0.351 | 0.351 |
| 17 | | | 0.354 | 0.351 |
| 18 | | | 0.353 | 0.346 |
| 19 | | | 0.356 | 0.353 |
| 20 | | | 0.355 | 0.348 |
| 21 | | | 0.358 | 0.349 |
| 22 | | | 0.357 | 0.350 |
| 23 | | | 0.355 | 0.352 |
| 24 | | | 0.352 | 0.352 |
| 25 | | | 0.353 | 0.351 |
| 26 | | | 0.352 | 0.351 |
| 27 | | | 0.353 | 0.357 |
| 28 | | | 0.362 | 0.351 |
| 29 | | | 0.351 | 0.348 |
| 30 | | | 0.361 | 0.354 |
| 31 | | | 0.355 | 0.348 |
| 32 | | | 0.356 | 0.349 |
| 33 | | | 0.358 | 0.349 |
| 34 | | | 0.357 | 0.342 |
| 35 | | | 0.355 | 0.346 |
| 36 | | | 0.355 | 0.356 |
| 37 | | | 0.350 | 0.351 |
| 38 | | | 0.356 | 0.354 |
| 39 | | | 0.353 | 0.352 |
| 40 | | | 0.354 | 0.351 |
| 41 | | | 0.354 | 0.357 |
| Avg | 30.6 | 30.0 | 0.354 | 0.351 |
| SD | 2.4 | 2.0 | 0.003 | 0.003 |

Table D.21
Subject 7 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.391 | 51.5 | 31.4 | 1.353 | 50.9 | 32.2 |
| 1.455 | 47.3 | 33.0 | 1.409 | 49.4 | 32.0 |
| 1.502 | 47.9 | 35.8 | 1.483 | 47.6 | 36.0 |
| 1.572 | 48.6 | 39.6 | 1.469 | 49.3 | 36.0 |
| 1.636 | 52.1 | 40.8 | 1.589 | 50.7 | 39.9 |

Table D.22
Subject 8 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.512 |
| 33% | 1.484 |
| 42% | 1.476 |
| 50% | 1.489 |
| 58% | 1.481 |
| 67% | 1.447 |
| 75% | 1.457 |
| 83% | 1.455 |

Table D.23
Subject 8 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 26.9 | 29.1 | 0.330 | 0.335 |
| 2 | 28.9 | 25.9 | 0.334 | 0.341 |
| 3 | 28.3 | 27.5 | 0.334 | 0.336 |
| 4 | 26.4 | 29.2 | 0.338 | 0.337 |
| 5 | 28.2 | 28.6 | 0.331 | 0.339 |
| 6 | 28.5 | 27.3 | 0.332 | 0.337 |
| 7 | 27.6 | 29.5 | 0.333 | 0.339 |
| 8 | 26.6 | 29.1 | 0.334 | 0.338 |
| 9 | 27.4 | 28.2 | 0.333 | 0.338 |
| 10 | 26.2 | 27.6 | 0.334 | 0.337 |
| 11 | | | 0.330 | 0.338 |
| 12 | | | 0.335 | 0.338 |
| 13 | | | 0.334 | 0.338 |
| 14 | | | 0.333 | 0.338 |
| 15 | | | 0.328 | 0.333 |
| 16 | | | 0.332 | 0.334 |
| 17 | | | 0.330 | 0.334 |
| 18 | | | 0.330 | 0.337 |
| 19 | | | 0.336 | 0.339 |
| 20 | | | 0.331 | 0.340 |
| 21 | | | 0.334 | 0.338 |
| 22 | | | 0.334 | 0.331 |
| 23 | | | 0.333 | 0.338 |
| 24 | | | 0.332 | 0.330 |
| 25 | | | 0.332 | 0.336 |
| 26 | | | 0.332 | 0.334 |
| 27 | | | 0.329 | 0.344 |
| 28 | | | 0.331 | 0.341 |
| 29 | | | 0.337 | 0.333 |
| 30 | | | 0.338 | 0.336 |
| 31 | | | 0.339 | 0.334 |
| 32 | | | 0.333 | 0.339 |
| 33 | | | 0.328 | 0.334 |
| 34 | | | 0.322 | 0.339 |
| 35 | | | 0.331 | 0.338 |
| 36 | | | 0.336 | 0.338 |
| 37 | | | 0.331 | 0.338 |
| 38 | | | 0.333 | 0.338 |
| 39 | | | 0.327 | 0.337 |
| 40 | | | 0.331 | 0.340 |
| 41 | | | 0.332 | 0.339 |
| 42 | | | 0.336 | 0.336 |
| 43 | | | 0.335 | 0.340 |
| Avg | 27.5 | 28.2 | 0.333 | 0.337 |
| SD | 1.0 | 1.1 | 0.003 | 0.003 |

Table D.24
Subject 8 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.323 | 39.9 | 21.1 | 1.316 | 39.1 | 20.7 |
| 1.381 | 38.1 | 23.6 | 1.373 | 38.5 | 23.8 |
| 1.450 | 36.4 | 25.6 | 1.450 | 36.5 | 24.3 |
| 1.493 | 37.0 | 26.7 | 1.487 | 37.6 | 24.2 |
| 1.551 | 38.6 | 28.3 | 1.544 | 38.0 | 29.1 |

Table D.25
Subject 9 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.436 |
| 33% | 1.416 |
| 42% | 1.404 |
| 50% | 1.416 |
| 58% | 1.424 |
| 67% | 1.424 |
| 75% | 1.426 |
| 83% | 1.430 |

Table D.26
Subject 9 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 20.5 | 18.5 | 0.342 | 0.347 |
| 2 | 20.1 | 19.8 | 0.350 | 0.345 |
| 3 | 18.8 | 21.0 | 0.347 | 0.343 |
| 4 | 19.5 | 20.6 | 0.348 | 0.345 |
| 5 | 19.7 | 21.7 | 0.347 | 0.346 |
| 6 | 20.6 | 21.7 | 0.341 | 0.342 |
| 7 | 21.3 | 21.0 | 0.350 | 0.346 |
| 8 | 20.3 | 20.2 | 0.348 | 0.346 |
| 9 | 20.5 | 19.0 | 0.347 | 0.346 |
| 10 | 19.6 | 20.7 | 0.346 | 0.346 |
| 11 | | | 0.344 | 0.346 |
| 12 | | | 0.342 | 0.343 |
| 13 | | | 0.345 | 0.344 |
| 14 | | | 0.346 | 0.343 |
| 15 | | | 0.347 | 0.343 |
| 16 | | | 0.351 | 0.343 |
| 17 | | | 0.345 | 0.343 |
| 18 | | | 0.348 | 0.347 |
| 19 | | | 0.347 | 0.346 |
| 20 | | | 0.347 | 0.347 |
| 21 | | | 0.350 | 0.343 |
| 22 | | | 0.350 | 0.340 |
| 23 | | | 0.350 | 0.347 |
| 24 | | | 0.350 | 0.343 |
| 25 | | | 0.346 | 0.343 |
| 26 | | | 0.342 | 0.343 |
| 27 | | | 0.334 | 0.348 |
| 28 | | | 0.338 | 0.347 |
| 29 | | | 0.347 | 0.349 |
| 30 | | | 0.345 | 0.345 |
| 31 | | | 0.347 | 0.343 |
| 32 | | | 0.354 | 0.342 |
| 33 | | | 0.349 | 0.344 |
| 34 | | | 0.350 | 0.345 |
| 35 | | | 0.346 | 0.350 |
| 36 | | | 0.346 | 0.347 |
| 37 | | | 0.341 | 0.345 |
| 38 | | | 0.349 | 0.346 |
| 39 | | | 0.347 | 0.346 |
| 40 | | | 0.349 | 0.346 |
| 41 | | | 0.349 | 0.343 |
| 42 | | | 0.345 | 0.349 |
| Avg | 20.1 | 20.4 | 0.346 | 0.345 |
| SD | 0.7 | 1.1 | 0.004 | 0.002 |

Table D.27
Subject 9 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.250 | 39.8 | 33.0 | 1.274 | 40.5 | 33.0 |
| 1.300 | 39.0 | 35.5 | 1.328 | 40.4 | 34.2 |
| 1.350 | 37.3 | 38.0 | 1.356 | 40.1 | 36.7 |
| 1.407 | 39.8 | 40.9 | 1.439 | 40.6 | 39.6 |
| 1.462 | 39.8 | 43.8 | 1.497 | 41.2 | 42.9 |

Table D.28
Subject 10 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.354 |
| 33% | 1.348 |
| 42% | 1.366 |
| 50% | 1.341 |
| 58% | 1.348 |
| 67% | 1.357 |
| 75% | 1.364 |
| 83% | 1.385 |

Table D.29
Subject 10 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 27.8 | 25.9 | 0.365 | 0.366 |
| 2 | 28.6 | 27.5 | 0.368 | 0.369 |
| 3 | 27.9 | 28.3 | 0.364 | 0.367 |
| 4 | 29.1 | 27.7 | 0.365 | 0.367 |
| 5 | 28.2 | 27.4 | 0.370 | 0.367 |
| 6 | 27.7 | 26.9 | 0.369 | 0.367 |
| 7 | 28.4 | 29.2 | 0.370 | 0.370 |
| 8 | 29.2 | 27.2 | 0.367 | 0.365 |
| 9 | 25.8 | 28.8 | 0.369 | 0.367 |
| 10 | 27.4 | 27.8 | 0.372 | 0.370 |
| 11 | | | 0.371 | 0.367 |
| 12 | | | 0.373 | 0.374 |
| 13 | | | 0.370 | 0.368 |
| 14 | | | 0.371 | 0.365 |
| 15 | | | 0.371 | 0.370 |
| 16 | | | 0.374 | 0.369 |
| 17 | | | 0.369 | 0.369 |
| 18 | | | 0.372 | 0.366 |
| 19 | | | 0.374 | 0.362 |
| 20 | | | 0.374 | 0.361 |
| 21 | | | 0.371 | 0.370 |
| 22 | | | 0.371 | 0.370 |
| 23 | | | 0.371 | 0.369 |
| 24 | | | 0.372 | 0.375 |
| 25 | | | 0.374 | 0.374 |
| 26 | | | 0.376 | 0.373 |
| 27 | | | 0.371 | 0.371 |
| 28 | | | 0.371 | 0.369 |
| 29 | | | 0.372 | 0.367 |
| 30 | | | 0.369 | 0.367 |
| 31 | | | 0.371 | 0.367 |
| 32 | | | 0.368 | 0.370 |
| 33 | | | 0.372 | 0.367 |
| 34 | | | 0.371 | 0.367 |
| 35 | | | 0.370 | 0.367 |
| 36 | | | 0.368 | 0.370 |
| 37 | | | 0.371 | 0.371 |
| 38 | | | 0.368 | 0.376 |
| 39 | | | 0.363 | 0.373 |
| Avg | 28.0 | 27.6 | 0.370 | 0.369 |
| SD | 1.0 | 0.9 | 0.003 | 0.003 |

Table D.30
Subject 10 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.374 | 45.2 | 32.1 | 1.367 | 46.7 | 34.2 |
| 1.434 | 42.7 | 32.9 | 1.428 | 45.1 | 35.7 |
| 1.501 | 41.5 | 34.2 | 1.480 | 44.9 | 33.3 |
| 1.556 | 42.0 | 35.6 | 1.485 | 44.4 | 36.3 |
| 1.614 | 43.6 | 40.0 | 1.548 | 45.3 | 36.6 |

Table D.31
Subject 11 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.495 |
| 33% | 1.470 |
| 42% | 1.489 |
| 50% | 1.487 |
| 58% | 1.481 |
| 67% | 1.492 |
| 75% | 1.487 |
| 83% | 1.484 |

Table D.32
Subject 11 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 22.2 | 23.2 | 0.365 | 0.366 |
| 2 | 25.5 | 26.2 | 0.368 | 0.369 |
| 3 | 25.0 | 26.3 | 0.364 | 0.367 |
| 4 | 25.5 | 24.3 | 0.365 | 0.367 |
| 5 | 26.2 | 24.5 | 0.370 | 0.367 |
| 6 | 24.2 | 26.0 | 0.369 | 0.367 |
| 7 | 26.2 | 24.4 | 0.370 | 0.370 |
| 8 | 24.4 | 25.1 | 0.367 | 0.365 |
| 9 | 26.9 | 24.4 | 0.369 | 0.367 |
| 10 | 25.8 | 26.5 | 0.372 | 0.370 |
| 11 | | | 0.371 | 0.367 |
| 12 | | | 0.373 | 0.374 |
| 13 | | | 0.370 | 0.368 |
| 14 | | | 0.371 | 0.365 |
| 15 | | | 0.371 | 0.370 |
| 16 | | | 0.374 | 0.369 |
| 17 | | | 0.369 | 0.369 |
| 18 | | | 0.372 | 0.366 |
| 19 | | | 0.374 | 0.362 |
| 20 | | | 0.374 | 0.361 |
| 21 | | | 0.371 | 0.370 |
| 22 | | | 0.371 | 0.370 |
| 23 | | | 0.371 | 0.369 |
| 24 | | | 0.372 | 0.375 |
| 25 | | | 0.374 | 0.374 |
| 26 | | | 0.376 | 0.373 |
| 27 | | | 0.371 | 0.371 |
| 28 | | | 0.371 | 0.369 |
| 29 | | | 0.372 | 0.367 |
| 30 | | | 0.369 | 0.367 |
| 31 | | | 0.371 | 0.367 |
| 32 | | | 0.368 | 0.370 |
| 33 | | | 0.372 | 0.367 |
| 34 | | | 0.371 | 0.367 |
| 35 | | | 0.370 | 0.367 |
| 36 | | | 0.368 | 0.370 |
| 37 | | | 0.371 | 0.371 |
| 38 | | | 0.368 | 0.376 |
| 39 | | | 0.363 | 0.373 |
| Avg | 25.2 | 25.1 | 0.370 | 0.369 |
| SD | 1.3 | 1.1 | 0.003 | 0.003 |

Table D.33
Subject 11 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.375 | 37.7 | 30.5 | 1.350 | 38.6 | 31.3 |
| 1.458 | 37.6 | 33.5 | 1.417 | 38.2 | 32.3 |
| 1.465 | 36.0 | 34.2 | 1.474 | 37.7 | 33.2 |
| 1.518 | 37.4 | 36.3 | 1.534 | 38.1 | 35.9 |
| 1.558 | 37.5 | 34.6 | 1.592 | 38.3 | 39.6 |

Table D.34
Subject 12 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.457 |
| 33% | 1.455 |
| 42% | 1.455 |
| 50% | 1.457 |
| 58% | 1.462 |
| 67% | 1.465 |
| 75% | 1.462 |
| 83% | 1.470 |

Table D.35
Subject 12 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 23.8 | 24.2 | 0.341 | 0.342 |
| 2 | 25.2 | 23.6 | 0.341 | 0.342 |
| 3 | 24.5 | 23.7 | 0.341 | 0.340 |
| 4 | 24.0 | 24.6 | 0.341 | 0.340 |
| 5 | 24.0 | 23.6 | 0.341 | 0.338 |
| 6 | 25.2 | 25.1 | 0.341 | 0.341 |
| 7 | 24.8 | 23.3 | 0.341 | 0.334 |
| 8 | 24.1 | 24.6 | 0.340 | 0.337 |
| 9 | 23.9 | 23.6 | 0.340 | 0.339 |
| 10 | 24.3 | 26.0 | 0.342 | 0.335 |
| 11 | | | 0.344 | 0.336 |
| 12 | | | 0.346 | 0.340 |
| 13 | | | 0.342 | 0.342 |
| 14 | | | 0.338 | 0.342 |
| 15 | | | 0.338 | 0.340 |
| 16 | | | 0.340 | 0.339 |
| 17 | | | 0.345 | 0.339 |
| 18 | | | 0.347 | 0.342 |
| 19 | | | 0.346 | 0.338 |
| 20 | | | 0.343 | 0.339 |
| 21 | | | 0.339 | 0.340 |
| 22 | | | 0.339 | 0.337 |
| 23 | | | 0.339 | 0.340 |
| 24 | | | 0.338 | 0.339 |
| 25 | | | 0.342 | 0.338 |
| 26 | | | 0.351 | 0.338 |
| 27 | | | 0.349 | 0.338 |
| 28 | | | 0.347 | 0.341 |
| 29 | | | 0.342 | 0.341 |
| 30 | | | 0.339 | 0.348 |
| 31 | | | 0.342 | 0.344 |
| 32 | | | 0.354 | 0.345 |
| 33 | | | 0.361 | 0.339 |
| 34 | | | 0.351 | 0.341 |
| 35 | | | 0.332 | 0.343 |
| 36 | | | 0.343 | 0.350 |
| 37 | | | 0.348 | 0.343 |
| 38 | | | 0.349 | 0.343 |
| 39 | | | 0.349 | 0.340 |
| 40 | | | 0.347 | 0.337 |
| 41 | | | 0.344 | 0.341 |
| 42 | | | 0.345 | 0.340 |
| 43 | | | 0.346 | 0.340 |
| Avg | 24.4 | 24.2 | 0.344 | 0.340 |
| SD | 0.5 | 0.9 | 0.005 | 0.003 |

Table D.36
Subject 12 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.292 | 54.6 | 29.6 | 1.278 | 58.2 | 28.8 |
| 1.346 | 53.0 | 30.6 | 1.332 | 57.1 | 35.0 |
| 1.405 | 51.1 | 33.4 | 1.389 | 52.2 | 34.0 |
| 1.456 | 53.5 | 36.4 | 1.440 | 56.7 | 37.6 |
| 1.514 | 54.1 | 36.5 | 1.500 | 58.2 | 34.2 |

Table D.37
Subject 13 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.404 |
| 33% | 1.380 |
| 42% | 1.380 |
| 50% | 1.397 |
| 58% | 1.390 |
| 67% | 1.397 |
| 75% | 1.392 |
| 83% | 1.387 |

Table D.38
Subject 13 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 26.8 | 26.8 | 0.360 | 0.356 |
| 2 | 25.4 | 27.5 | 0.357 | 0.358 |
| 3 | 27.1 | 27.6 | 0.354 | 0.356 |
| 4 | 25.0 | 26.1 | 0.357 | 0.356 |
| 5 | 25.3 | 25.8 | 0.354 | 0.358 |
| 6 | 26.4 | 27.5 | 0.356 | 0.362 |
| 7 | 25.5 | 26.1 | 0.355 | 0.364 |
| 8 | 26.9 | 26.9 | 0.354 | 0.359 |
| 9 | 27.2 | 24.2 | 0.353 | 0.358 |
| 10 | 25.4 | 27.9 | 0.354 | 0.356 |
| 11 | | | 0.356 | 0.359 |
| 12 | | | 0.357 | 0.360 |
| 13 | | | 0.356 | 0.364 |
| 14 | | | 0.356 | 0.364 |
| 15 | | | 0.361 | 0.363 |
| 16 | | | 0.354 | 0.363 |
| 17 | | | 0.355 | 0.363 |
| 18 | | | 0.356 | 0.363 |
| 19 | | | 0.353 | 0.360 |
| 20 | | | 0.355 | 0.360 |
| 21 | | | 0.358 | 0.360 |
| 22 | | | 0.355 | 0.360 |
| 23 | | | 0.358 | 0.361 |
| 24 | | | 0.352 | 0.366 |
| 25 | | | 0.360 | 0.364 |
| 26 | | | 0.355 | 0.361 |
| 27 | | | 0.357 | 0.357 |
| 28 | | | 0.361 | 0.356 |
| 29 | | | 0.360 | 0.359 |
| 30 | | | 0.356 | 0.359 |
| 31 | | | 0.352 | 0.361 |
| 32 | | | 0.359 | 0.357 |
| 33 | | | 0.351 | 0.357 |
| 34 | | | 0.352 | 0.359 |
| 35 | | | 0.353 | 0.361 |
| 36 | | | 0.354 | 0.361 |
| 37 | | | 0.354 | 0.358 |
| 38 | | | 0.357 | 0.359 |
| 39 | | | 0.354 | 0.360 |
| 40 | | | 0.351 | 0.362 |
| 41 | | | 0.359 | 0.360 |
| Avg | 26.1 | 26.6 | 0.356 | 0.360 |
| SD | 0.9 | 1.1 | 0.003 | 0.003 |

Table D.39
Subject 13 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.361 | 51.0 | 28.0 | 1.358 | 50.6 | 28.9 |
| 1.414 | 49.5 | 30.2 | 1.417 | 49.9 | 30.7 |
| 1.480 | 46.0 | 32.6 | 1.474 | 46.8 | 32.0 |
| 1.479 | 49.3 | 35.2 | 1.533 | 50.1 | 33.4 |
| 1.596 | 50.6 | 35.5 | 1.596 | 51.3 | 36.4 |

Table D.40
Subject 14 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.475 |
| 33% | 1.439 |
| 42% | 1.460 |
| 50% | 1.457 |
| 58% | 1.442 |
| 67% | 1.447 |
| 75% | 1.444 |
| 83% | 1.460 |

Table D.41
Subject 14 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 25.0 | 24.0 | 0.338 | 0.345 |
| 2 | 25.6 | 23.8 | 0.339 | 0.339 |
| 3 | 25.3 | 23.0 | 0.336 | 0.341 |
| 4 | 22.5 | 25.4 | 0.337 | 0.343 |
| 5 | 26.8 | 24.1 | 0.339 | 0.341 |
| 6 | 25.2 | 23.0 | 0.341 | 0.342 |
| 7 | 23.9 | 24.1 | 0.341 | 0.341 |
| 8 | 25.6 | 25.2 | 0.338 | 0.341 |
| 9 | 22.5 | 22.3 | 0.332 | 0.343 |
| 10 | 24.1 | 25.1 | 0.337 | 0.339 |
| 11 | | | 0.343 | 0.336 |
| 12 | | | 0.343 | 0.347 |
| 13 | | | 0.342 | 0.337 |
| 14 | | | 0.343 | 0.340 |
| 15 | | | 0.337 | 0.342 |
| 16 | | | 0.336 | 0.339 |
| 17 | | | 0.337 | 0.342 |
| 18 | | | 0.338 | 0.336 |
| 19 | | | 0.340 | 0.340 |
| 20 | | | 0.342 | 0.339 |
| 21 | | | 0.342 | 0.338 |
| 22 | | | 0.338 | 0.338 |
| 23 | | | 0.332 | 0.335 |
| 24 | | | 0.336 | 0.341 |
| 25 | | | 0.343 | 0.337 |
| 26 | | | 0.336 | 0.339 |
| 27 | | | 0.339 | 0.338 |
| 28 | | | 0.342 | 0.338 |
| 29 | | | 0.342 | 0.338 |
| 30 | | | 0.343 | 0.338 |
| 31 | | | 0.337 | 0.338 |
| 32 | | | 0.348 | 0.338 |
| 33 | | | 0.342 | 0.338 |
| 34 | | | 0.345 | 0.342 |
| 35 | | | 0.340 | 0.337 |
| 36 | | | 0.338 | 0.339 |
| 37 | | | 0.338 | 0.338 |
| 38 | | | 0.338 | 0.336 |
| 39 | | | 0.340 | 0.339 |
| 40 | | | 0.337 | 0.336 |
| 41 | | | 0.336 | 0.334 |
| 42 | | | 0.338 | 0.339 |
| 43 | | | 0.335 | 0.333 |
| Avg | 24.7 | 24.0 | 0.339 | 0.339 |
| SD | 1.4 | 1.0 | 0.003 | 0.003 |

Table D.42
Subject 14 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.352 | 55.0 | 38.2 | 1.300 | 55.5 | 32.7 |
| 1.412 | 53.5 | 37.7 | 1.357 | 54.2 | 37.6 |
| 1.478 | 51.2 | 43.6 | 1.412 | 53.0 | 39.1 |
| 1.473 | 51.1 | 42.9 | 1.470 | 54.4 | 43.8 |
| 1.593 | 54.8 | 48.5 | 1.525 | 55.2 | 41.9 |

Table D.43
Subject 15 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.452 |
| 33% | 1.444 |
| 42% | 1.430 |
| 50% | 1.424 |
| 58% | 1.416 |
| 67% | 1.414 |
| 75% | 1.407 |
| 83% | 1.412 |

Table D.44
Subject 15 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 30.3 | 26.5 | 0.338 | 0.357 |
| 2 | 29.6 | 25.6 | 0.341 | 0.358 |
| 3 | 27.7 | 25.6 | 0.338 | 0.356 |
| 4 | 30.5 | 27.4 | 0.337 | 0.355 |
| 5 | 31.4 | 26.0 | 0.343 | 0.356 |
| 6 | 27.9 | 26.6 | 0.339 | 0.357 |
| 7 | 29.2 | 27.2 | 0.338 | 0.359 |
| 8 | 30.8 | 29.1 | 0.342 | 0.357 |
| 9 | 27.1 | 26.5 | 0.340 | 0.357 |
| 10 | 30.7 | 27.4 | 0.342 | 0.358 |
| 11 | | | 0.346 | 0.352 |
| 12 | | | 0.344 | 0.352 |
| 13 | | | 0.335 | 0.350 |
| 14 | | | 0.342 | 0.352 |
| 15 | | | 0.340 | 0.357 |
| 16 | | | 0.340 | 0.353 |
| 17 | | | 0.338 | 0.349 |
| 18 | | | 0.333 | 0.349 |
| 19 | | | 0.340 | 0.354 |
| 20 | | | 0.338 | 0.357 |
| 21 | | | 0.338 | 0.348 |
| 22 | | | 0.335 | 0.348 |
| 23 | | | 0.336 | 0.355 |
| 24 | | | 0.340 | 0.356 |
| 25 | | | 0.335 | 0.349 |
| 26 | | | 0.338 | 0.360 |
| 27 | | | 0.337 | 0.350 |
| 28 | | | 0.337 | 0.355 |
| 29 | | | 0.337 | 0.355 |
| 30 | | | 0.330 | 0.354 |
| 31 | | | 0.339 | 0.355 |
| 32 | | | 0.337 | 0.354 |
| 33 | | | 0.336 | 0.357 |
| 34 | | | 0.336 | 0.357 |
| 35 | | | 0.338 | 0.358 |
| 36 | | | 0.338 | 0.355 |
| 37 | | | 0.340 | 0.355 |
| 38 | | | 0.338 | 0.354 |
| 39 | | | 0.336 | 0.353 |
| 40 | | | 0.335 | 0.356 |
| 41 | | | 0.338 | 0.353 |
| Avg | 29.5 | 26.8 | 0.338 | 0.354 |
| SD | 1.5 | 1.0 | 0.003 | 0.003 |

Table D.45
Subject 15 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.355 | 54.9 | 25.9 | 1.315 | 56.0 | 23.8 |
| 1.415 | 54.2 | 27.7 | 1.368 | 53.6 | 26.2 |
| 1.475 | 52.0 | 28.2 | 1.407 | 52.7 | 27.2 |
| 1.533 | 53.0 | 29.0 | 1.483 | 56.7 | 28.4 |
| 1.588 | 55.6 | 33.9 | 1.536 | 55.9 | 30.3 |

Table D.46
Subject 16 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.470 |
| 33% | 1.452 |
| 42% | 1.439 |
| 50% | 1.434 |
| 58% | 1.416 |
| 67% | 1.429 |
| 75% | 1.421 |
| 83% | 1.424 |

Table D.47
Subject 16 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 26.3 | 25.6 | 0.346 | 0.357 |
| 2 | 29.4 | 30.3 | 0.340 | 0.356 |
| 3 | 28.6 | 25.7 | 0.343 | 0.356 |
| 4 | 29.7 | 28.3 | 0.343 | 0.353 |
| 5 | 25.9 | 26.1 | 0.343 | 0.358 |
| 6 | 29.6 | 28.5 | 0.343 | 0.356 |
| 7 | 26.8 | 25.2 | 0.337 | 0.357 |
| 8 | 29.8 | 28.6 | 0.342 | 0.359 |
| 9 | 26.5 | 24.5 | 0.339 | 0.356 |
| 10 | 29.5 | 29.5 | 0.340 | 0.357 |
| 11 | | | 0.342 | 0.362 |
| 12 | | | 0.337 | 0.359 |
| 13 | | | 0.339 | 0.356 |
| 14 | | | 0.339 | 0.356 |
| 15 | | | 0.336 | 0.352 |
| 16 | | | 0.336 | 0.353 |
| 17 | | | 0.338 | 0.357 |
| 18 | | | 0.341 | 0.355 |
| 19 | | | 0.335 | 0.360 |
| 20 | | | 0.328 | 0.356 |
| 21 | | | 0.336 | 0.350 |
| 22 | | | 0.336 | 0.357 |
| 23 | | | 0.336 | 0.355 |
| 24 | | | 0.336 | 0.352 |
| 25 | | | 0.339 | 0.350 |
| 26 | | | 0.347 | 0.356 |
| 27 | | | 0.334 | 0.355 |
| 28 | | | 0.341 | 0.355 |
| 29 | | | 0.335 | 0.355 |
| 30 | | | 0.342 | 0.352 |
| 31 | | | 0.338 | 0.359 |
| 32 | | | 0.336 | 0.355 |
| 33 | | | 0.339 | 0.356 |
| 34 | | | 0.341 | 0.349 |
| 35 | | | 0.341 | 0.356 |
| 36 | | | 0.340 | 0.352 |
| 37 | | | 0.340 | 0.354 |
| 38 | | | 0.340 | 0.353 |
| 39 | | | 0.340 | 0.351 |
| 40 | | | 0.342 | 0.356 |
| 41 | | | 0.340 | 0.357 |
| Avg | 28.2 | 27.2 | 0.339 | 0.355 |
| SD | 1.6 | 2.0 | 0.004 | 0.003 |

Table D.48
Subject 16 step-by-step stiffness and stride rate

| Initial Measurement | | | Final Measurement | | |
|---|---|---|---|---|---|
| Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) | Stride Rate (Hz) | $\dot{V}O_2$ (ml/kg/min) | Vertical Stiffness (kN/m) |
| 1.288 | 63.8 | 40.5 | 1.201 | 60.5 | 40.5 |
| 1.398 | 59.4 | 44.7 | 1.253 | 59.4 | 42.4 |
| 1.346 | 57.3 | 44.1 | 1.305 | 58.4 | 43.7 |
| 1.464 | 61.0 | 44.2 | 1.418 | 60.9 | 45.1 |
| 1.512 | 61.5 | 48.5 | 1.419 | 61.2 | 48.5 |

Table D.49
Subject 17 initial and final means

| Percent of run completed | Preferred Stride Rate (Hz) |
|---|---|
| 8% | 1.399 |
| 33% | 1.362 |
| 42% | 1.357 |
| 50% | 1.366 |
| 58% | 1.380 |
| 67% | 1.364 |
| 75% | 1.364 |
| 83% | 1.364 |

Table D.50
Subject 17 Data

| | Stiffness (kN/m) | | Step Time (s) | |
|---|---|---|---|---|
| Step | Initial | Final | Initial | Final |
| 1 | 31.6 | 28.7 | 0.374 | 0.385 |
| 2 | 31.1 | 30.8 | 0.372 | 0.383 |
| 3 | 30.4 | 31.2 | 0.373 | 0.381 |
| 4 | 30.4 | 30.3 | 0.376 | 0.385 |
| 5 | 30.7 | 32.2 | 0.370 | 0.381 |
| 6 | 31.5 | 31.9 | 0.378 | 0.383 |
| 7 | 27.8 | 30.6 | 0.370 | 0.379 |
| 8 | 33.1 | 30.1 | 0.379 | 0.381 |
| 9 | 29.7 | 33.2 | 0.379 | 0.381 |
| 10 | 31.2 | 29.4 | 0.377 | 0.385 |
| 11 | | | 0.373 | 0.382 |
| 12 | | | 0.364 | 0.383 |
| 13 | | | 0.376 | 0.381 |
| 14 | | | 0.367 | 0.381 |
| 15 | | | 0.372 | 0.379 |
| 16 | | | 0.368 | 0.380 |
| 17 | | | 0.366 | 0.383 |
| 18 | | | 0.373 | 0.382 |
| 19 | | | 0.362 | 0.381 |
| 20 | | | 0.377 | 0.385 |
| 21 | | | 0.371 | 0.384 |
| 22 | | | 0.370 | 0.386 |
| 23 | | | 0.375 | 0.384 |
| 24 | | | 0.369 | 0.383 |
| 25 | | | 0.364 | 0.390 |
| 26 | | | 0.371 | 0.383 |
| 27 | | | 0.362 | 0.381 |
| 28 | | | 0.372 | 0.392 |
| 29 | | | 0.371 | 0.383 |
| 30 | | | 0.375 | 0.383 |
| 31 | | | 0.370 | 0.385 |
| 32 | | | 0.373 | 0.385 |
| 33 | | | 0.367 | 0.384 |
| 34 | | | 0.370 | 0.384 |
| 35 | | | 0.370 | 0.384 |
| 36 | | | 0.373 | 0.384 |
| 37 | | | 0.383 | 0.384 |
| 38 | | | 0.367 | 0.384 |
| Avg | 30.8 | 30.8 | 0.372 | 0.383 |
| SD | 1.4 | 1.3 | 0.005 | 0.003 |

Table D.51
Subject 17 step-by-step stiffness and stride rate

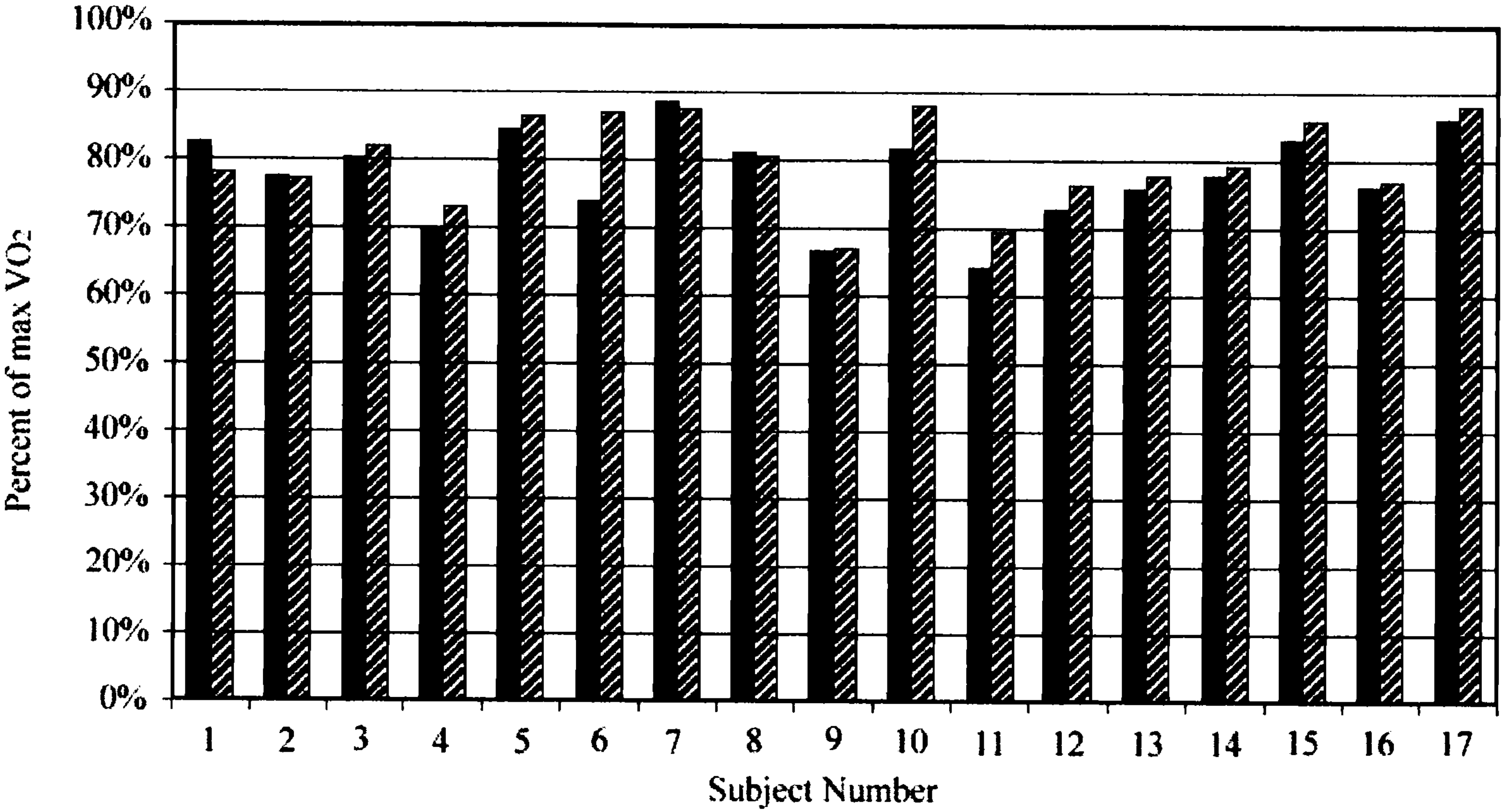

Figure D.1
Initial and final percent of maximum oxygen uptake for each subject.

| Subject | Initial $R^2$ | Final $R^2$ |
|---|---|---|
| 1 | 0.90 | 0.40 |
| 2 | 0.48 | 0.62 |
| 3 | 0.94 | 0.75 |
| 4 | 0.45 | 0.39 |
| 5 | 0.66 | 0.42 |
| 6 | 0.96 | 0.85 |
| 7 | 0.70 | 0.83 |
| 8 | 0.95 | 0.79 |
| 9 | 0.97 | 0.75 |
| 10 | 0.52 | 0.95 |
| 11 | 1.00 | 0.95 |
| 12 | 0.30 | 0.90 |
| 13 | 0.72 | 0.61 |
| 14 | 0.63 | 0.64 |
| 15 | 0.91 | 0.88 |
| 16 | 0.80 | 0.48 |
| 17 | 0.59 | 0.97 |
| Mean | 0.73 | 0.72 |
| SD | 0.22 | 0.2 |

Table D.52
R2 values for second-degree polynomial fits of oxygen uptake versus stride rate.

# APPENDIX E

# TREADMILL RECALIBRATION

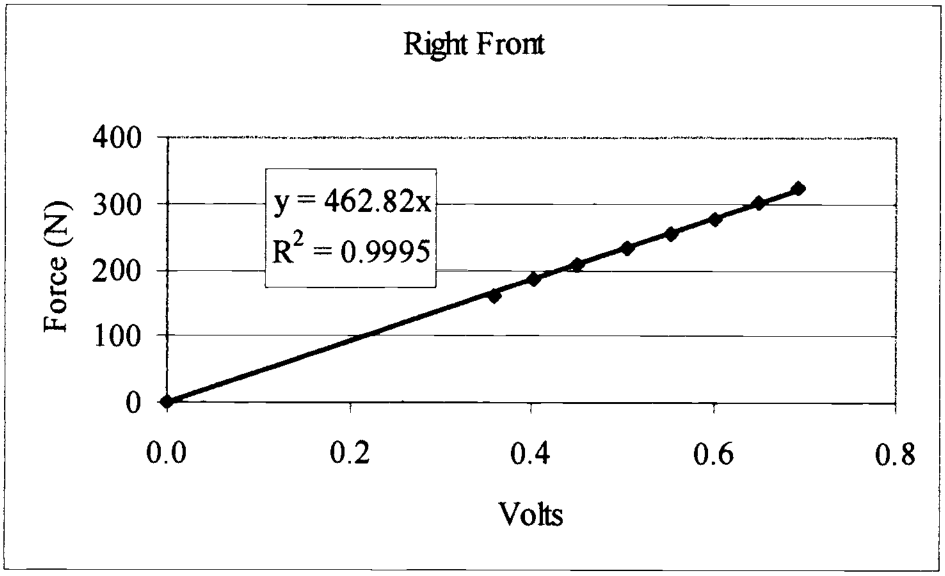

Figure E.1

Right front transducer

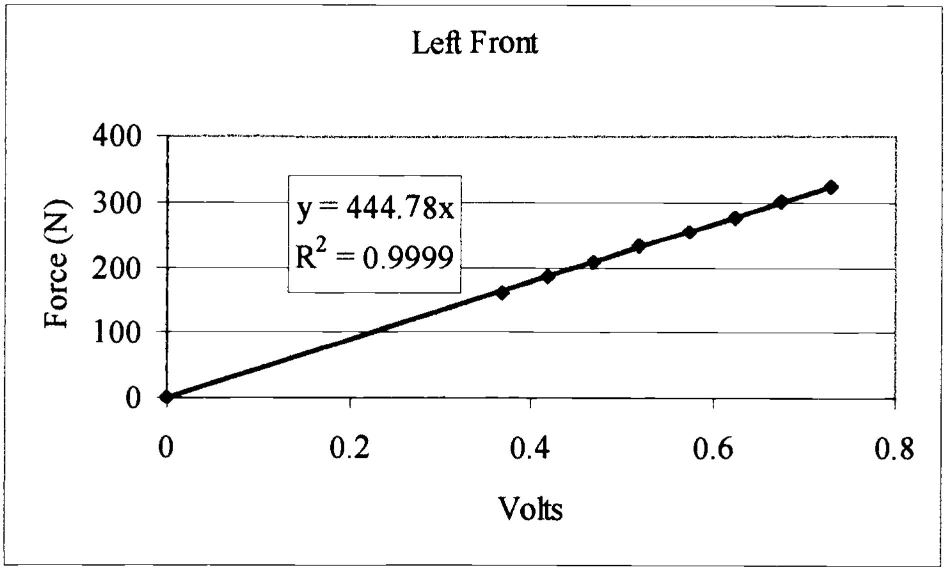

Figure E.2

Left front transducer

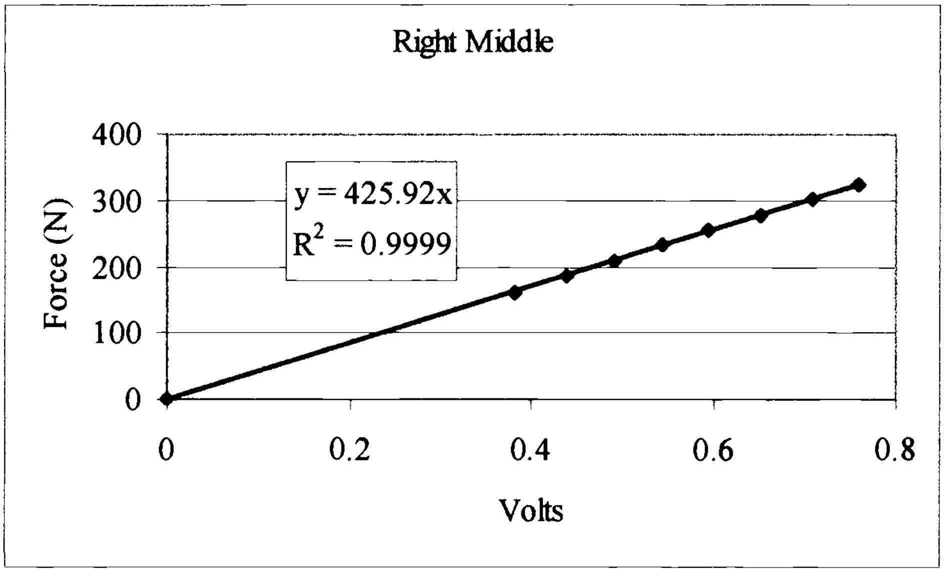

Figure E.3

Right middle transducer

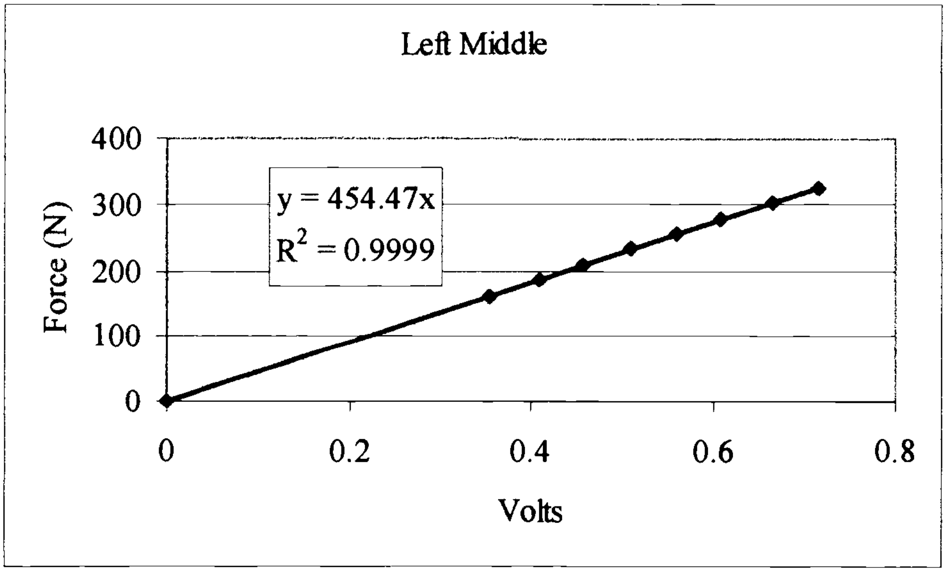

Figure E.4

Right middle transducer

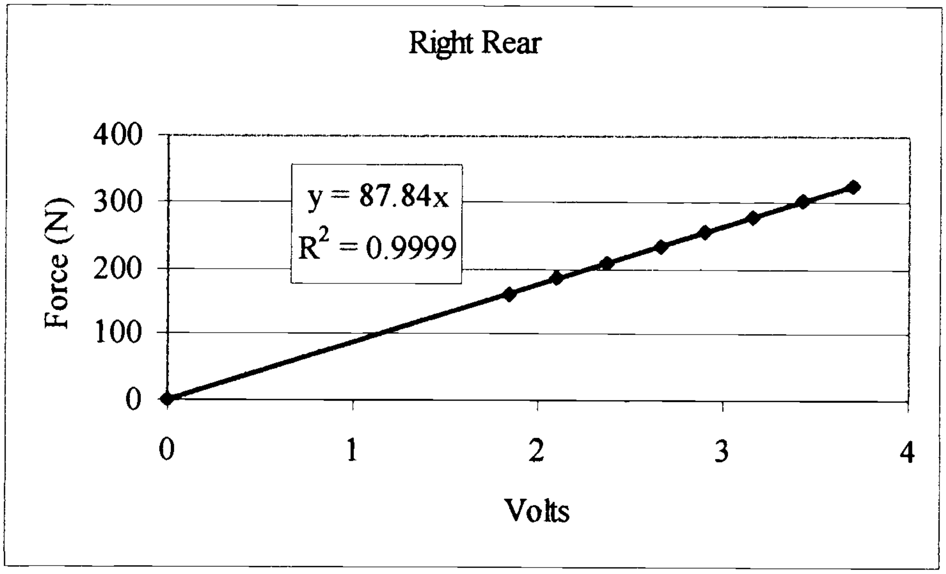

Figure E.5

Right rear transducer

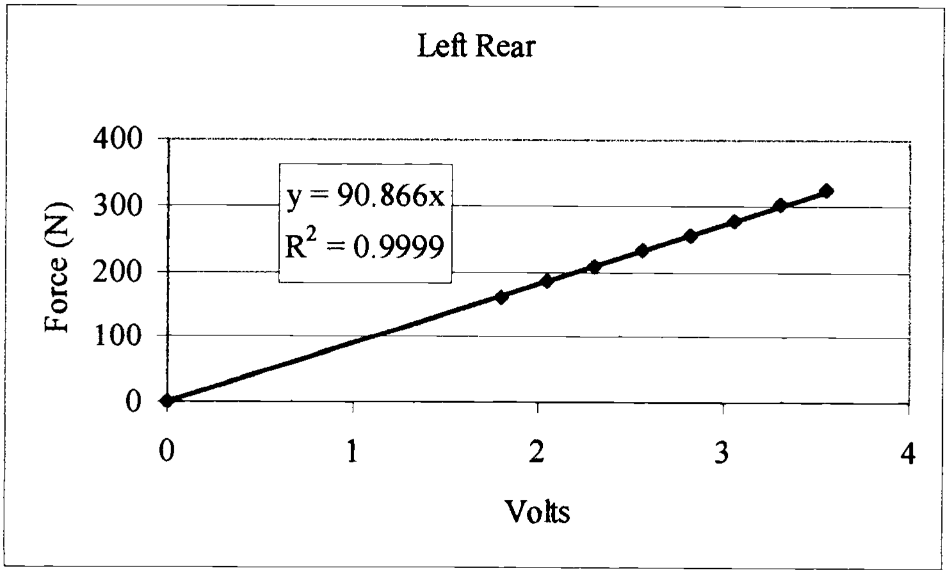

Figure E.6

Left rear transducer

| Position | Left Front | Right Front | Left Middle | Right Middle | Left Rear | Right Rear |
|---|---|---|---|---|---|---|
| Channel | A | B | C | D | E | F |
| Original Calibration (mV/N) | 2.34 | 2.291 | 2.322 | 2.298 | 11.441 | 11.982 |
| Current Calibration (mV/N) | 2.242 | 2.14 | 2.205 | 2.341 | 10.956 | 11.395 |

Table E.1

Treadmill calibration