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Weighted running: Effect on impact and oxygen consumption

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WEIGHTED RUNNING: EFFECT ON IMPACT AND OXYGEN CONSUMPTION

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ABSTRACT

Weighted Running: Effect on Impact and Oxygen Consumption

by

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The purpose of this study was to investigate if runners adjust running style based on impact magnitude instead of running economy while wearing 30% added trunk weight. Runners ran overground at a self-selected pace with and without 30% added trunk weight. Impact magnitudes and other force parameters were analyzed. Runners also ran on a treadmill with 30% added trunk weight at their preferred stride frequency (PSF) and at ±10% PSF. Oxygen consumption (VO_2) and PSF were recorded. VO_2 and PSF were greater during nonweighted compared to weighted running ($p<0.05$). During weighted running, VO_2 was greater when running at the -10% PSF than the PSF, but not different than the +10% PSF. The slightly greater stride frequency during weighted running compared to nonweighted running may be a strategy to keep F1 magnitudes constant concurrent with maintaining and economical gait pattern. It was concluded that individuals optimized on VO_2 and impact concurrently.

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CHAPTER I

INTRODUCTION

Running is a common form of cardiovascular exercise as well as a competitive sport. Finding the exact components of a running style that maximizes performance and/or decreases the chance for injury would be of interest to marathon runners as well as recreational runners. Running is a relatively basic form of exercise that does not need excessive equipment or specific knowledge about the sport. Almost anyone is capable of using running for exercise, however, there are many different factors that contribute to a runner's ability. There are basically two dominant components comprising a running style. The first component consists of physiological parameters, such as rate of oxygen consumption (VO_2), or running economy. Ever since exercise was found to be beneficial health wise, running has been a popular form of exercise to improve cardiovascular health and to promote weight loss. Therefore, there is a wealth of research investigating physiological parameters during running. However, with the running boom of the 70's, it was also determined that running is connected with overuse injuries (James, Bates and Ostemig, 1978; Hreljac, Marshall, and Hume, 2000). Therefore, the second component of running style consists of a group of biomechanical parameters, such as ground impact.

The term "running economy" is commonly used when discussing the physiological factors of running and is defined as the steady-state oxygen consumption (VO_2) for a given running speed (Conley & Krahenbuhl, 1980). The less oxygen needed

to perform a submaximal run at a given velocity, the more economical the runner. Running economy is highly correlated to distance running performance (Conley and Krahenbuhl, 1980); therefore, finding the exact components that comprise an economical running style would be beneficial to elite distance runners as well as competitive and recreational runners wishing to improve running performance. Frederick (1983) pointed out that even a relatively small change in running economy may be very important in running performance. It is logical to think that a 2% increase in running economy would equate to a 2% increase in performance. While a 2% increase in performance may seem small, it is important to apply this to actual running times. At a world-record 10K pace a 2% improvement in running economy would be equal to about 32 seconds. At world-record marathon pace, the difference would be more than 2 minutes (Cavanagh, Biomechanics of running). This example illustrates the importance of understanding running economy when discussing running performance.

Previous research generally supports the idea that the body adopts a running style that optimizes VO_2, that is, uses that least amount of oxygen (Cavanagh and Williams, 1982). Many factors contribute to running economy, such as age, gender, impact and fatigue (Morgan and Craib, 1992). An important way individuals minimize VO_2 is to run with a stride frequency-stride length (SF-SL) combination that results in the most economical running style for a given running speed. Running velocity is the product of SF and SL. Therefore, as SF increase, SL decreases, and as SL increases, SF decreases. When running at a set speed, if an individual runs at a SF other than the preferred stride frequency (PSF) oxygen consumption generally increases. Figure 1 illustrates the classic U-shaped curve for SF versus VO_2. During normal treadmill running, VO_2 seems to be

the most important criterion the body uses to choose a running style, since it is minimized in the typical runner.

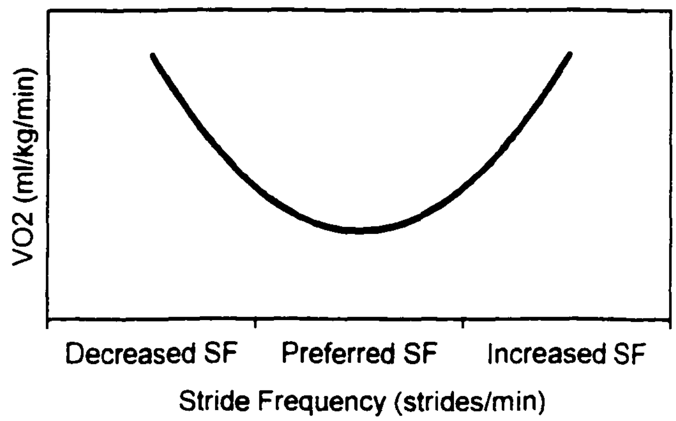


Figure 1. The VO_2- SF relationship.

Under certain conditions, however, a runner may select a running style that does not result in the least VO_2. For example, the magnitude of impact between the ground and foot may be an important factor determining running style in some instances. It seems reasonable to suspect that the individual considers the effect impact with the ground has on the body, as well as VO_2, when choosing a running style.

Impact magnitude may increase through a variety of ways. Newton's second law of motion states that a force (impact) of an object is equal to the product of the object's mass and acceleration (F=ma). Therefore, the two possible factors that may change impact forces are to change the body's mass or acceleration while running. Adding weight to the body may potentially increase impact magnitude if other parameters, such as running style, stay the same. On the other hand, if running style changes, acceleration will potentially change, resulting in increased impact magnitudes. While Newton's

second law is true in theory concerning added mass with inanimate objects, there is a limited amount of research investigating the relationship between added weight and impact magnitudes in humans while running.

Running has been associated with a high incidence of overuse injuries (James et al., 1978; Hreljac et al., 2000). It has been estimated that between 27% and 70% of runners suffer an overuse injury during any 1-year period (Hreljac et al. 2000). Hreljac et al (2000) studied possible factors contributing to overuse injuries in runners. They found that overuse injuries were less prevalent in runners with low impact forces while running. It is thought that the repetitive impact force applied through the foot to the body is a possible cause for running injuries. Since high impact forces are thought to be associated with injury it seems reasonable to expect the body to minimize these forces. While this seems logical, Hamill, Derrick and Holt (1995) found that impact, as quantified by ground reaction forces, was not minimized at the PSF-PSL combination for a given running speed. Since impact was not minimized in Hamill et al (1995), this suggests that the body must therefore be able to tolerate a certain degree of impact without becoming injured. Furthermore, Hamill et al. (1995) reported that impact was not minimized but VO_2 was at the PSF-PSL. These findings of Hamill et al. (1995) support the idea that individuals optimize on VO_2, rather than impact. This is the case during normal treadmill running, however, when impact increases, the body must be able to regulate impact magnitudes. As previously explained, excessive impact may lead to injury; therefore, if the body was unable to accommodate to the increased impact, it would seem that running injuries would be more prevalent. When impact becomes extreme, the optimality criterion used to choose a running style may shift from predominantly physiological factors to biomechanical factors.

If impact becomes excessive, the body has two primary methods to accommodate to the increases in impact. The first is by changing the SF-SL combination. Impact is known to decrease as SL decreases (Derrick et al., 1998). Since SL and SF have an inverse relationship, one strategy to decrease excessive impact at the same running speed could be to increase SF (Cooke, 1991). This may be one strategy; however, Claremont (1988) and Martin (1985) have found that added ankle weight (possibly increasing impact) did not significantly change stride frequency, meaning that VO_2, not impact, for this study, was probably the important factor in choosing a running style, even with added weight.

The second way individuals are able to regulate impact forces is to adopt a more compliant running style. As running compliancy increases (and leg stiffness decreases) there is the potential to "absorb" more impact energy. An increased running compliance is characterized by the knee going through more flexion during the stance phase, which results in an increase in muscle activity. Nigg and Liu (1999) studied the effects of leg stiffness on impact forces. They concluded that an increase in muscle activity, or "muscle tuning", is a possible strategy to change vertical GRF. An increase in muscle activity may decrease impact forces. This "softer" running style decreases impact on the body, however, by running more compliantly, muscular activity increases. An increase in muscle activity requires more oxygen and therefore, results in an increase in VO_2. Researching compliant running styles, McMahon, Valiant and Frederick (1987) studied a running style described as "groucho running." This running style is characterized as excessive knee flexion during the stance phase of running, which is one definition of a more compliant running style. They found that as knee flexion (i.e., running compliancy)

increased stance phase time (ST) also increased. Therefore, ST may be used as an indicator of running compliancy.

If impact is great enough to potentially cause injury, the body has the ability to regulate impact forces by either increasing SF or running compliancy. If an individual adopts a new running style in response to increased impact, then, under these circumstances, impact is the optimality criterion used to choose a running style. If this is the case, then the body decreases impact and disregards the fact that VO_2 is not being minimized. Presently, it is unclear under what conditions a person chooses to optimize on impact instead of VO_2.

Purpose of the Study

During running, it is generally accepted that runners tend to choose a running style that optimizes VO_2 (Hamill, et al., 1995). However, there may be situations when factors other than VO_2 become more important. For example, impact magnitude may reach a perceived dangerous level resulting in an altered running style. Therefore, the purpose of the study was to find if impact becomes a predominant optimality criterion used to choose a running style.

Hypotheses

It is hypothesized that:

1. Oxygen consumption while wearing 30% added trunk weight will not be optimized.
2. Impact magnitudes F1 at 30% added trunk weight will be equal to the impact magnitudes at 0% added trunk weight.

3. F2 magnitudes at 30% added trunk weight will be the same as at 0% added trunk weight.
4. F_{zavg} will remain the same for 0% and 30% added trunk weight.
5. SF will remain the same for 0% and 30% added trunk weight.
6. ST will increase with 30% added trunk weight as compared to 0% added trunk weight.

Limitations of the Study

The limitations to the study are as follows:

1. Video analysis was not used in this study; therefore, leg stiffness based on kinematics and kinetics was not quantified. Stance time was used as an indicator of running compliancy (leg stiffness).
2. The force plate introduces some instrumentation limitations. GRF were measured at 1000 HZ, which limits the accuracy of the data.
3. The running speed across the force plate was controlled using two infrared timing cells. Only trials ±5% of 2.1 ± 0.3 m s^{-1} were used for analysis, therefore, the results of the study should only be applied to speeds of 2.64 ± 0.3 m s^{-1}.
4. All subjects had previous treadmill running experience, and were free from injury. Also, all subjects were heel-toe runners, as opposed to toe runners. Toe runners have been shown to produce different vertical GRF curves than heel-toe runners. This limits the external validity of the study to healthy, heel-toe runners with previous running experience.

Definitions

Running economy – the amount of oxygen needed to run at a given speed: $VO_{2submax}$

VO_2 – the rate of oxygen consumption (ml/kg/min).

Impact forces – forces that result from a collision of two objects, reaching their maximum earlier than 50 ms after the first contact of the foot with the ground (Nigg, 1995).

Ground reaction forces (GRF) – a measurement of ground impact: during running, the GRF represents the acceleration of the center of mass (a=F/m).

F1 – the first peak in the GRF curve: occurs during the first 50 ms of the stance phase

F2 – the second peak in the GRF curve: occurs about midstance

Average force – the average ground impact force during the stance phase of running

Stance phase time (ST) – the time period of foot contact with the ground during running

Stride frequency (SF) – the number of strides per minute at a certain speed

Preferred stride frequency (PSF) – the SF an individual runs at: usually corresponds the minimal VO_2.

Stride length (SL) – the length of a stride at a certain running speed.

Running velocity = SF x SL

Preferred stride length (PSL) – the SL an individual runs at a particular speed: related to PSF

Optimality criterion – criterion used to choose a running style: the criterion used for this study was VO_2 or impact

Optimization – the process of choosing a running style that minimizes VO_2 or impact

Strategy/accommodation – a change in running style that accounts for perturbations in the running environment

Lower extremity stiffness – the amount of hip, knee, and ankle flexion during stance

CHAPTER 2

LITERATURE REVIEW

VO_2 is usually the factor optimized under normal running conditions. However. there may be situations when other factors become more important. For. example. impact magnitude may reach a perceived dangerous level resulting in an altered running style. Although it has been hypothesized that impact is related to running injuries. (Hrelejac et al.. 2000) there is minimal research indicating whether runners optimized on impact. Therefore. the purpose of the study was to investigate if impact could be a predominant optimality criterion that determines a running style.

There have been two general areas of study focusing on running. A number of researchers have concentrated their research on the physiological aspects of running. such as the correlations between heart rate. ventilation. and body weight with VO_2 (Pate. Macera. Bailey. Bartoli. and Powell. 1992). As running gained popularity as a competitive sport. as well as a mode of exercise. there was a concurrent increase in the number of running related injuries. Therefore. other scientists became involved in running research by studying impact forces and kinematic variables and their possible connection with running injuries (Hrelijac. Marshall. and Hume. 2000). Very few studies however. have investigated the interaction between the two parameters of physiology and biomechanics pertaining to running. There is a wealth of information on factors that affect the physiological factors of running. such as gender (Daniels and Daniels. 1992).

altitude (Morgan and Craib, 1992), and added weight (Cavanagh and Kram, 1989). Previous research has also studied the biomechanical aspects of running, which looked at impact magnitudes by changing stride length (SL) (Derrick, Hamill and Caldwell, 1998), surfaces (Dixon, Collop and Batt, 2000), speed (Frederick and Hagy, 1986), and grade (Swanson and Caldwell, 2000). However, no studies have looked at the effects of added trunk weight on impact magnitudes while running. Therefore, the purpose of the study was to investigate whether impact, not VO_2, becomes a predominant optimality criterion used to choose a running style.

Physiological Factors

The term running economy is widely used when discussing the physiological aspects of running styles. Daniels and Daniels (1991) defined running economy as the relationship between the rate of oxygen consumption (VO_2) and velocity of running, or as the aerobic demand of running. Conley and Krahenbuhl (1980) defined running economy as the steady-state oxygen consumption ($ml \cdot kg^{-1} min^{-1}$) for a standardized running speed. Both of these definitions support the concept that as the amount of oxygen consumed for a given running speed is reduced, the runner is considered to be more economical. The definition given by Conley et al (1980) will be used for this study. Conley et al (1980) investigated the relationship between distance running performance and running economy. They concluded that when comparing individuals of equal or near equal VO_{2max} values, distance running performance was strongly correlated to running economy.

Holt, Hamill and Andres (1990) studied the body as a combination of complex oscillatory processes. They concluded that the underlying goal of locomotion is self-

optimization, in the form of minimal metabolic cost. In other words, they concluded that individuals tended to adopt a running style that minimized VO_2. There are many factors that may potentially affect this self-optimization, or VO_2 minimization. Morgan and Craib (1992) described several physiological factors, such as body temperature, muscle fiber type, heart rate and ventilation, gender, air resistance, altitude, fatigue, and level of training that could contribute to economical running styles. Another major contributor of an economical running style frequently studied is the stride frequency-stride length (SF-SL) combination used while running. A classic single subject study by Hogberg (1952) concluded that individuals run at a preferred stride frequency-preferred stride length (PSF-PSL) combination that minimizes oxygen consumption. The most economical SL is always very close to, if not exactly, the freely chosen one when the subject is well trained. Cavanagh and Williams (1982) replicated Hogberg's study, testing more subjects. They came to the same conclusions, that VO_2 was usually minimized at the PSL, and that when SL deviates from the freely chosen SL, oxygen consumption increases.

In addition to changing running style, VO_2 magnitude is affected by adding load to the body. The American College of Sports Medicine (ACSM) has developed equations used to predict VO_2 ($ml \cdot kg^{-1} min^{-1}$) while running based the running speed and grade. If the predicted VO_2 was expressed in $L \cdot min^{-1}$, and then readjusted for total system weight ($L \cdot min^{-1}$), the equation predicts that the increase in VO_2 would be proportional to the added load to the body. While the ACSM prediction equations were developed to predict VO_2 under normal running condition, Epstein, Stroschein, and Pandolf (1987) developed an equation for predicting VO_2 while running with added trunk weight. Their conclusions support the hypothesis that VO_2 should increase in proportion

to the weight added to the body during running. That is, there is a linear relationship between added trunk weight and VO_2 during running. Davies (1980) studied the effects 10% added trunk weight had on the VO_2 of children. He found that VO_2 increased in direct proportion to the added weight, which is in agreement with both ACSM and Epstein et al (1987). Cook, McDonagh, Nevill, and Davies (1991) also studied the effects added weight has on the rate of oxygen consumption. However, they found there was not a significant increase in VO_2 with up to 10% added trunk weight (0.1% increase in VO_2 in adults). Cavanagh and Kram (1989) studied the effects added ankle weight has on VO_2, and concluded that it was six times more costly (higher VO_2) to run with weight on the ankles, than weight on the trunk. Claremont and Hall (1988), and Martin (1985) also studied the effect extremity loading had on VO_2. Claremont et al. (1988) weighted the ankles of runners and found that there was a 5-10% increase in VO_2 with 1kg ankle weights. Martin (1985) added 0.25 kg and 0.5 kg weights to the ankles and to the thighs. He found that the added weight on the thigh produced a 1.7% and 3.5% increase in VO_2 for the 0.25 and 0.5 kg weights respectively. He also found that there was a 3.3% and a 7.2% increase when the weight was added to the ankles. This supports Cavanagh's idea that it is 6 times more metabolically costly to add weight to the ankles than to the trunk (Cavangh and Kram, 1989).

The literature suggests that VO_2 is affected by running style (i.e. SL and SF) and by added trunk weight. This study will investigate whether VO_2 continues to be optimized with added trunk weight, or, whether individuals change running style (e.g. increase SF) in response to added trunk weight.

Presently, there is no empirical evidence that VO_2 is minimized while running with added trunk weight. This hypothesis could be tested by having runners run at faster

and slower SF compared to the PSF. If VO_2 is not minimized at PSF with added weight, it would seem that the runner is optimizing on another factor. If running at ±10% PSF while wearing 30% added trunk weight does not produce a U-shaped curve when plotting VO_2 and SF, this indicates that the individual is running on a different portion of the U-shaped curve, and is therefore, optimizing on something other than VO_2. The other optimizing factor could be impact, which will be revealed by analyzing the impact magnitudes of running with 0% and 30% added trunk weight.

Biomechanical Factors

While running economy seems to be the dominant factor in choosing a running style during normal treadmill running and important in performance, impact magnitudes have been of interest to researchers because of the possible association with injuries. Hamill, Derrick and Holt (1995) reported that VO_2, and not impact, was minimized during running. While impact was not minimized, it is possible to potentially change impact magnitudes while running. There are many circumstances that could potentially change impact magnitudes, including running surface, kinematics, speed, and added weight (Farley & Ferris, 1998 Review). Derrick et al (1998) studied how kinematic changes in running style affected impact. They showed that as SL increased, shock attenuation increased, as a result of increased ground impact.

During running, the foot contacts the ground with a certain amount of force. This force is the sum of the accelerations of all parts of the body, with a force exerted through the foot on the ground. Newton's third law of motion states that for every action there is an equal and opposite reaction. Therefore, the force the body exerts on the ground is equivalent to the force the ground exerts back on the body. This ground reaction force is

measured by a force plate and referred to as a ground reaction force (GRF). A typical GRF curve during running is illustrated in figure 2. The curve usually has two distinct peaks during heel-toe running. The first impact peak is labeled F1 (passive peak) and represents the maximum force within 50 ms of foot contact (Nigg, Cole, and Bruggemann, 1995). The second portion of the curve is labeled F2 (active peak) and usually occurs during midstance.

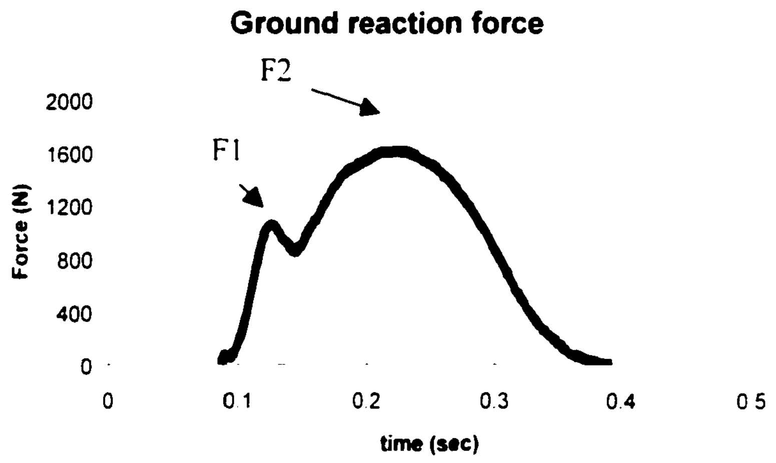


Figure 2. A typical ground reaction force (GRF)

Impact magnitude may increase through a variety of ways. Newton's second law of motion states that a force (impact) of an object is equal to the product of the object's mass and acceleration (F=ma). Acceleration is defined as the change in velocity over a certain time period $((v_f-v_i)/t)$. For example, consider an impact situation where v_i is the velocity just prior to ground contact, and v_f is the final velocity equal to zero (i.e. object is stopped). The force the ground exerts on the object to stop the downward velocity would increase if mass increased with no change in other parameters (i.e. acceleration). Likewise, if the change in velocity increased with no change in m, or t, F would increase.

If the time period that it took velocity to go to zero decreased. F would increase given no change in other parameters. During running, impact velocity (v_i) may increase by increasing flight time, which could happen as SL increases (Gerritsen, van den Bogert, Nigg, 1995). Running on a stiffer surface could result in a decrease the time to change velocity (i.e. increase acceleration). Finally, if the mass of the object increases, F should increase according to Newton's second law (F=ma), if there was no change in acceleration (i.e. v_i, v_f, or t). While Newton's second law is true in theory concerning added mass with inanimate objects, there is a limited amount of research investigating the relationship between added weight and impact magnitudes in humans while running. In conclusion, three ways to potentially affect magnitude of impact is to change acceleration (or a component that determines acceleration) or to increase mass.

Frederick and Hagy (1986) studied the effect of different running speeds on GRF magnitudes. They specifically looked at impact peaks (F1) and active peaks (F2) of the GRF curves during running at speeds of 3.35-4.47 m/s. In addition to the GRF data, many kinematic variables, such as contact angle between the hip and foot, dorsiflexion angle and body mass, were analyzed for their relative contributions to the vertical GRF peaks. The authors concluded that there was a positive correlation between peak impact forces and running speed and also with body mass. This means that as speed increased, impact forces increased as well. Also, impact peak magnitudes increased with body mass.

Dixon, Collop, and Batt (2000) investigated surface effects on GRF magnitude and lower extremity kinematics while running. The authors hypothesized that impact forces would be reduced while running on surfaces with increased cushioning properties. In order to study the effects running surfaces have on impact forces, subjects ran over three

different running surfaces of varying cushioning properties while GRF data were collected. The authors concluded that there was no significant difference in peak impact force between the three running surfaces. The lack of change in impact force between surfaces was partly explained by kinematic analysis adjustments, such as increased knee flexion at ground contact while running on the stiffer surfaces compared to softer surfaces. Increased knee flexion during ground contact is one definition of increased running compliancy (McMahon et al, 1987). Therefore, the results of Dixon and colleague's study suggest that increased running compliancy is a possible kinematic adaptation in running style in order to reduce impact forces while running.

Simpson, Bates, and McCaw (1998) studied how added load to the ankles affected GRF while running. They concluded that individuals responded differently to the added ankle weight. For example, some subjects had an increased impact magnitude while others had a decreased impact magnitude in response to the added ankle weight. The authors concluded that there are two very different strategies that individuals use to account for an added load to the body, Newtonian and neuromuscular. The Newtonian response and the neuromuscular response are the extreme ends of a continuum of strategies. There are numerous combinations of these two responses that may be employed by an individual to adapt to an external load. As stated previously, the first method for adapting to added weight is to ignore the weight and have an increase in impact; the second is to change the running style to accommodate for the extra weight and ultimately decrease impact magnitudes. High impact forces have been hypothesized as a cause of injury (Mechelen, 1992). The results from Simpson et al (1988) and the fact that not everyone becomes injured while running supports the concept that the body has mechanisms to accommodate to excess impact. Since these studies show that it is

possible to accommodate for extra weight placed on the body, the next question is how does the body accommodate.

Strategies to Regulate Impact Magnitudes

There are two predominant methods the body may use to regulate impact forces while running: 1) adjust SL and SF; 2) change running stiffness. Cooke et al (1991) studied the effect of added trunk weight up to 10% body weight on impact magnitude. They concluded that the body adapted to the extra weight by increasing SF, which may potentially decrease impact, however, impact was not measured.

Davies (1980) studied the effects added weight had on the gait patterns and metabolic costs of children. However, in contrast to Cooke et al. (1991), Davies (1980) found that SF did not change with up to 10% added trunk weight. Claremont et al (1988) and Martin (1985) studied the effects of added ankle weight on VO_2 and SF. Both of these studies reported that there was no significant change in SF or SL, however, there was a tendency to decrease SF in response to added ankle weight.
Although these studies did not quantify GRF, Derrick et al (1998) reported that F1 decreased with an increase in SF (decrease in SL), when speed was maintained. Likewise, Mercer, Devita, Derrick, and Bates (ISB, 1999) reported that impact attenuation was sensitive to SL changes. That is, if SL increased, impact attenuation increased as a result of increased ground impact.

In addition to increasing SF, another important way individuals regulate impact forces is by increasing running compliancy, in other words decrease lower extremity stiffness. McMahon et al (1987) studied a compliant running style called "groucho running" characterized by extreme knee flexion during the stance phase of running. The

results of this study displayed that F2 (maximum force near midstance) did not increase, and actually decreased in the groucho running condition. He also found that F1 did not change for the groucho running condition. Since the impact magnitudes did not change during groucho running, the subjects did not change the initial heel contact. However, the decrease in F2 magnitudes demonstrates that there was an accommodation during the remainder of the stance phase after initial ground contact.

While groucho running was found to decrease F2 magnitudes, McMahon et al (1987) also concluded that this running style was metabolically costly. Groucho running was found to be up to 50% more metabolically costly than normal running. Therefore, while increased running compliancy decreased F2 magnitudes, oxygen consumption increased.

Another study supporting the idea that running compliance increases oxygen consumption was conducted by Heise and Martin (1998). They looked at the correlation between leg stiffness and running economy. The leg can be modeled as a simple, linear spring (Farley and Gonzales, 1996). The stiffness of a spring is represented by the spring constant "k". Therefore, if the lower extremity is modeled as a spring, $K_{vertical}$ equals the stiffness of the leg. It is calculated by the equation: $K_{vert}=F_{max}/\Delta y$, where Δy is the change in vertical position of the center of mass during the stance phase of running. K_{vert} is dependent on the individual's running style. Farley and Gonzales (1996) reported that runners who displayed a more compliant running style were less economical. They concluded that there was an inverse relationship between the vertical spring constant of the body and aerobic demand. This indicates that less economical runners have more compliant running styles during ground contact.

Since VO_2 seems to be the factor usually optimized under normal running, the purpose of this study is to find if impact becomes a predominant optimality criterion when choosing a running style.

CHAPTER 3

METHODOLOGY AND DATA DESCRIPTION

VO_2 is usually the factor optimized under normal running conditions. However. there may be situations when other factors become more important. For. example. impact magnitude may reach a perceived dangerous level resulting in an altered running style. Therefore. the purpose of the study was to find if impact becomes a predominant optimality criterion used to choose a running style. Physiological and biomechanical aspects of running were used to determine the optimizing factor during running. More specifically. the rate of oxygen consumption (VO_2). vertical ground reaction force (GRF) data. stride frequency (SF). and stance phase time (ST) were evaluated during running.

Subjects

Ten healthy active subjects (10 females: mean age 25±5.25 years: mean ht 66.1 ± 2.13 inches: mean BW 144.89 ± 12.6 lbs: mean body fat 26.14% ± 4.36) participated in the study. All subjects had previous treadmill running experience and no orthopedic injuries six months prior to testing. All subjects were heel-toe runners and wore a standard running shoe model during testing. The study was approved by the University Human Subjects Board prior to testing. and all subjects gave voluntary informed consent prior to testing.

Instrumentation

Level running was performed on a Precor 9.4 treadmill. Prior to the start of testing, each subject self-selected a comfortable running speed. Subjects were instructed to choose a speed that they could maintain for about 45 minutes with occasional 5-minute rest periods interspersed within the testing period. This speed was used to complete all testing conditions for that subject.

Oxygen consumption was measured using a TEEM 100 gas analyzer, which was calibrated according to the manufacturer's directions before each subject was tested. Expired air was sampled continuously, and the average values over a 20 second period were recorded.

Stride frequency (SF) was calculated while the subject ran on the treadmill by recording the time to complete 20 strides. The average time of three trials was used to calculate SF at the self-selected running speed.

Ground reaction force (GRF) data were collected using a force plate (Kistler, model #9865B) that was level with the ground. GRF data were recorded at 1000 HZ. The components of the GRF that were analyzed were stance phase time (ST), magnitude of the impact peak (F1), active peak (F2), and the average force over ST (F_{avg}).

A weighted vest was used to increase trunk weight. The weight was evenly distributed around the subject's trunk using a weighted vest (Performance Wear) with removable 0.5 lb weights. The vest was secured loose enough as to not restrict breathing, however, tight enough as to not affect running style. The magnitude of added weight for the weighted trials was calculated from the subject's pre-exercise weight.

Lange calipers were used to measure percent body fat.

All testing was conducted in the Exercise Physiology/Biomechanics laboratory.

Experimental Procedure

Before the experimental procedure began, height, weight, and percent body fat were measured and recorded. Body fat was measured by Lange calipers in accordance to ACSM procedures. The sum of three sites (abdomen, ilium, and tricep) was used to calculate percent body fat. The subject self-selected a running speed which was then used throughout the entire experimental procedure. The study was then conducted in two separate experiments, both occurring on the same day immediately following each other.

Experiment 1

Subjects performed 8 overground running trials across a force plate at the self-selected speed. The running speed was measured using two infrared timing cells set 3-meters apart on either side of the force plate. Only trials that were ±5% of the self-selected running speed without obvious alterations to running stride were used for analysis. In addition, observation of anterior-posterior impulse during ground contact ensured that only running trials with no obvious change in horizontal velocity were included. Each subject completed 8 acceptable trials of GRF for the 0% and 30% added weight conditions.

Experiment 2

Subjects completed four run conditions on the treadmill at the same self-selected running speed as in experiment one. Each condition lasted 5-7 minutes, which included a 2-minute walking warm-up period for each condition. The four conditions consisted 1) 0% added weight at PSF (PSF_{NW}), 2) 30% added body weight at PSF (PSF_W), 3) 30%

added body weight at +10% PSF_W, and 4) 30% added body weight at −10% PSF_W. VO_2 data were recorded at 20-second intervals throughout the entire run condition. PSF was determined at 0% and 30% added body weight: ±10% PSF_W while wearing 30% added weight was then calculated based on PSF_W. During condition 3 and 4, subjects were instructed to run to the beat of a metronome set at ±10% PSF_W, while VO_2 was collected. Sufficient time was allowed between run conditions to minimize fatigue.

Data Reduction

VO_2 was measured continuously and the average values over a 20 second period were recorded for analysis. The average measurement of the last 1-2 minutes of the 3-5 minute run period was calculated as the running economy for the self-selected running speed, for that particular weighted condition.

F1 was determined as the first peak in the GRF that occurred within the first 50-ms after foot contact. F2 was determined as the maximum force that occurred after F1. F_{avg} was calculated as the average force over the stance phase.

Stance phase time (ST) was derived from the GRF. An impact value above 20 N was used as a criteria to identify heel contact and a value below 20 N was used to determine toe-off. The time between heel contact and toe-off was considered ST.

Stance phase time (ST) was used as an indicator of lower extremity stiffness. A decreased ST indicated a higher lower extremity stiffness. Custom laboratory software programs were written (MATlab 5.4) to analyze GRF data.

Body fat was calculated using the Jackson and Pollock sum of three-sites equation. The equation used is shown below.

JP-3: Sum=[Suprailiac]+[Abdomen]+[Tricep], (in mm)

Percent fat = 0.41563 (Σ3) – 0.00112 ($\Sigma 3^2$) + 0.03661(AGE) + 4.03653

Statistics

Statistical Hypothesis

7. VO_2 will be equal at 0% and 30% added trunk weight.
8. F1 will be equal at 0% and 30% added trunk weight.
9. F2 will be equal at 0% and 30% added trunk weight.
10. F_{avg} will be equal at 0% and 30% added trunk weight.
11. SF will be equal at 0% and 30% added trunk weight.
12. ST will be equal at 0% and 30% added trunk weight.

Statistical Tests

The dependent variables of interest were VO_2, F1, F2, F_{avg}, SF and ST. The independent variables were added weight, and stride frequency. Mean values were calculated across trials for each run condition. VO_2 was analyzed using a one-way repeated measures ANOVA on the subject means. In tests that resulted in a significant F-ratio ($P < 0.05$), a Tukey's multiple comparison test was performed to identify the location of the significant differences. In addition, the impact data were analyzed for significant differences using a paired t-test.

CHAPTER 4

DATA ANALYSIS

During running, it is generally accepted that runners tend to choose a running style that optimizes VO_2 (Hamill et al., 1995). However, there may be situations when runners optimize on factors other than VO_2. For example, impact magnitude may reach a perceived dangerous level resulting in an altered running style. Therefore, the purpose of the study was to find if impact becomes a predominant optimality criterion used to choose a running style.

Two experiments were completed: 1) investigation of impact magnitude during running with and without added weight during overground running; 2) investigation of VO_2 during running with and without added weight during treadmill running.

Speed

Running speed was self-selected before the start of Experiment 1, and was the same for both experiments. The average speed was 2.1 ± 0.3 $m \cdot sec^{-1}$ (Table 1).

Experiment 1

Impact Force (F1)

Of the ten subjects tested, two subjects (subjects 1 and 7) were excluded from the impact analysis since F1 was not consistently observed. This resulted in an n of 8 for the impact analysis, however, subjects 1 and 7 were included in the F2, F_{zavg}, ST,

Table 1. Running speeds in $m \cdot s^{-1}$ for each subject. Each subject used the same speed for each experiment.

Subject	$m \cdot s^{-1}$
1	1.8
2	2.6
3	1.9
4	2.2
5	1.9
6	2.0
7	1.9
8	2.2
9	2.0
10	2.7
Mean	2.1
Standard deviation	±0.3

VO_2, and SF analysis. Impact force (i.e. F1) was not different between the PSF_{NW} and the PSF_W condition (Figure 3, $t(7) = 0.33$, $p=0.752$). Table 2 summarizes F1 magnitudes for each subject.

Active Peak Force (F2)

F2 was different between conditions (Figure 4, $t(9)=-10.86$, $p<0.001$). F2 was greater during PSF_W (2.55 ±0.28 BW) compared to PSF_{NW} (2.17 ±0.24 BW). Table 3 summarizes the peak F2 magnitudes for each subject.

Average Vertical Force (F_{zavg})

F_{zavg} was different between conditions (Figure 5, $t(9)=-9.86$, $p<0.001$). F_{zavg} was greater during PSF_W (1.39±0.15 BW) compared to PSF_{NW} (1.23±0.16 BW). Table 4 summarizes the peak F_{zavg} magnitudes for each subject.

Stance Time

Stance time (ST) was different between conditions (Figure 6, $t(9)=-7.25$, $p<0.001$). ST was greater during PSF_W (0.380±0.057 s) compared to PSF_{NW} (0.337±0.050 sec). Table 5 summarizes the average stance time magnitudes for each subject.

Table 2. F1 magnitudes for each subject during running during PSF_{NW} and PSF_W conditions. Subjects 1 and 7 were excluded from the F1 analysis.

Subject	F1 PSF_{NW} normalized to BW	F1 PSF_W normalized to BW
1	—	—
2	1.77	1.68
3	1.11	1.27
4	1.37	1.53
5	1.31	1.26
6	1.69	1.65
7	—	—
8	1.38	1.33
9	0.99	1.13
10	1.55	1.16
Mean	1.40	1.37
Standard deviation	±0.27	±0.21

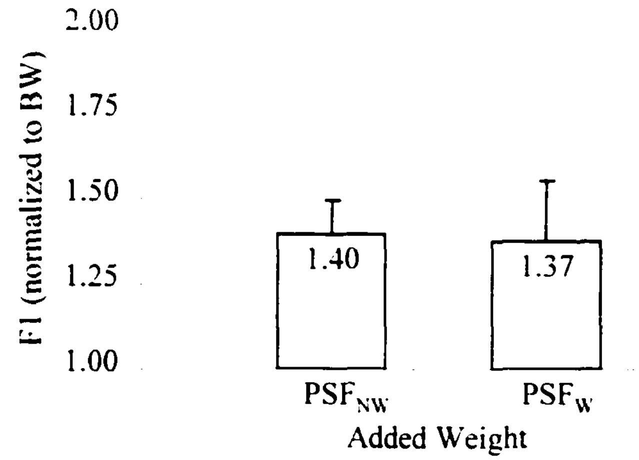


Figure 3. Group means and standard error bars for F1 magnitudes during PSF_{NW} and PSF_W conditions. There was no difference in F1 between conditions ($p>0.05$).

Table 3. F2 magnitudes for each subject during PSF_{NW} and PSF_W conditions.

Subject	PSF_{NW} normalized to BW	PSF_W normalized to BW
1	1.69	1.99
2	2.39	2.84
3	2.15	2.53
4	1.89	2.38
5	2.25	2.47
6	2.43	3.01
7	2.19	2.51
8	2.06	2.51
9	2.21	2.50
10	2.45	2.76
Mean	2.17	2.55
Standard deviation	±0.24	±0.28

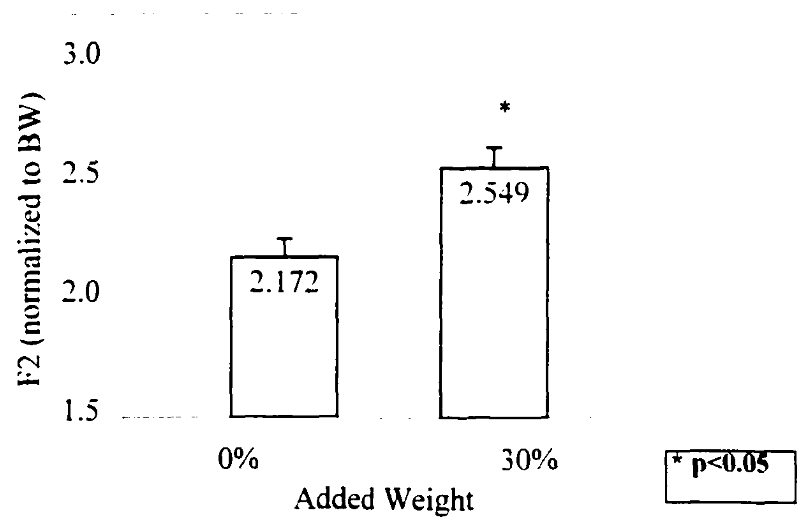


Figure 4. Group mean and standard error bars for F2 magnitudes during running for PSF_{NW} and PSF_W conditions.

Table 4. F_{zavg} magnitudes for each subject during running for PSF_{NW} and PSF_W conditions.

Subject	PSF_{NW} Normalized to BW	PSF_W normalized to BW
1	0.99	1.18
2	1.43	1.60
3	1.06	1.26
4	1.07	1.29
5	1.34	1.51
6	1.40	1.60
7	1.22	1.27
8	1.18	1.34
9	1.23	1.37
10	1.38	1.49
Average	1.23	1.39
Standard deviation	±0.16	±0.15

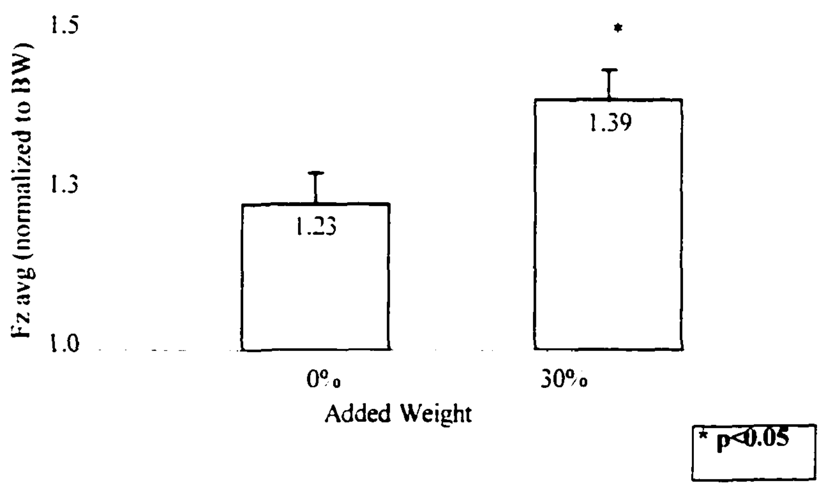


Figure 5. Group mean and standard error bars for F_{zavg} during PSF_{NW} and PSF_W condition

Table 5. Average stance time (sec) for each subject during PSF_{NW} and PSF_W conditions.

Subject	PSF_{NW} (s)	PSF_W (s)
1	0.438	0.496
2	0.272	0.301
3	0.385	0.419
4	0.347	0.383
5	0.342	0.391
6	0.304	0.339
7	0.330	0.414
8	0.347	0.369
9	0.342	0.370
10	0.268	0.313
Mean	0.337	0.380
Standard deviation	±0.050	±0.057

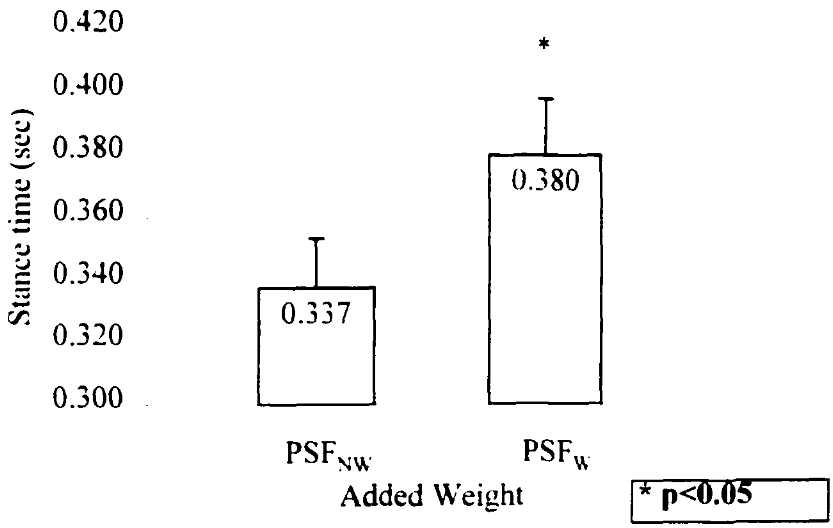


Figure 6. Group mean and standard error bars for stance time during the PSF_{NW} and PSF_W running condition.

Experiment 2

Oxygen Consumption (VO_2)

VO_2 was different across conditions (Figure 7, $F(3,27)=64.229$, $p<0.001$). Using planned comparisons, it was determined that VO_2 during the PSF_W condition was 22.3% greater compared to VO_2 during PSF_{NW} condition ($p<0.05$); VO_2 during PSF_W was lower compared to VO_2 during -10% PSF_W condition ($p<0.05$); VO_2 during PSF_W condition was not significantly different from the VO_2 during the $+10\%$ PSF_W condition ($p<0.05$). Table 6 summarizes VO_2 data for each subject during all conditions.

Stride Frequency

Stride frequency (SF) was significantly different between PSF_{NW} and PSF_W conditions (Figure 8, $t(9)=-4.08$, $p=0.003$). SF was greater during the PSF_W (1.37 ± 0.08 strides·sec^{-1}) compared to PSF_{NW} (1.32 ± 0.06 strides·sec^{-1}). Table 7 summarizes the stride frequency for each subject.

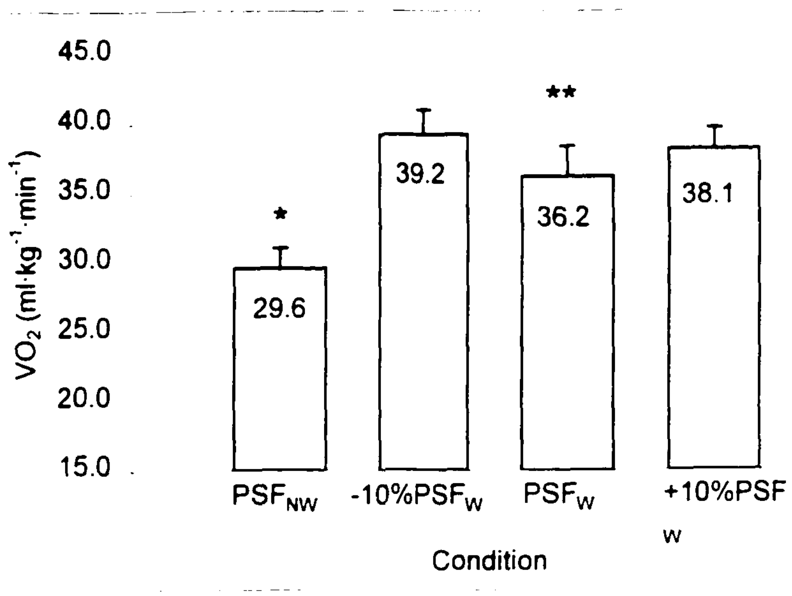


Figure 7. Group mean and standard error bars for VO_2 during all running conditions.

Note: * PSF_{NW} significantly different than all weighted conditions
**PSF_W significantly different than $-10\%PSF_W$, but not different than $+10\%PSF_W$

Table 6. VO_2 (ml·kg^{-1}min^{-1}) for each subject during PSF_{NW}, PSF_W, -10%PSF_W and +10%PSF_W running conditions.

Subject	PSF_{NW} (ml·kg^{-1}min^{-1})	-10% PSF_W (ml·kg^{-1}min^{-1})	PSF_W (ml·kg^{-1}min^{-1})	+10% PSF_W (ml·kg^{-1}min^{-1})
1	23.8	29.6	24.3	29.8
2	36.2	46.4	47.4	42.4
3	24.4	32.6	31.0	33.5
4	30.3	40.9	41.3	43.9
5	30.1	39.9	37.3	39.4
6	32.8	44.1	38.3	39.4
7	25.1	35.9	31.1	34.8
8	27.6	37.9	34.2	35.7
9	28.6	38.5	33.5	37.0
10	36.9	46.2	43.7	45.1
Mean	29.6	39.2	36.2	38.1
Standard deviation	±4.6	±5.6	±6.8	±4.9

Table 7. Average stride frequency (strides/sec) for all subjects during the PSF_{NW} and PSF_{W} conditions.

Subject	PSF_{NW} (strides/sec)	PSF_{W} (strides/sec)
1	1.28	1.26
2	1.39	1.48
3	1.31	1.36
4	1.37	1.38
5	1.25	1.31
6	1.23	1.27
7	1.32	1.39
8	1.34	1.35
9	1.31	1.38
10	1.39	1.47
Mean	1.32	1.37
Standard deviation	±0.06	±0.08

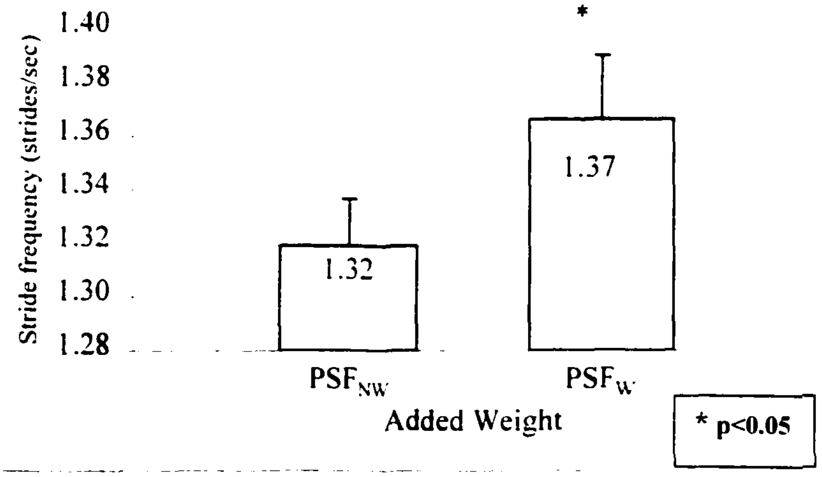


Figure 8. Mean stride frequency and standard error bars during PSF_{NW} and PSF_{W} condition

CHAPTER 5

CONCLUSIONS AND RECOMENDATIONS

During running, it is generally accepted that runners tend to choose a running style that optimizes VO_2 (Hamill, et al., 1995). However, there may be situations when factors other than VO_2 become more important. For example, impact magnitude may reach a perceived dangerous level resulting in an altered running style. Therefore, the purpose of the study was to find if impact becomes a predominant optimality criterion used to choose a running style.

Experiment 1

Experiment 1 investigated the effect of 30% added trunk weight on the GRF during running. Subjects choose to run at an average speed of 2.1 ± 0.3 $m \cdot s^{-1}$, and completed 8 acceptable running trials across the force plate for both the weighted (19.76 ± 1.71 kg of added weight) and nonweighted conditions.

Impact Force (F1)

During running, F1 represents the impact between the foot and the ground, and typically occurs during the first 25-50 msec of the stance phase of running (Nigg et al., 1995). The time in which the impact occurs is extremely short in duration following ground contact (25-50 msec), therefore, the magnitude of the impact peak is determined primarily by muscle activation and joint kinematics/kinetics before the foot contacts the ground (Heise & Martin, 1998). That is, the body does not have time to adjust

kinematics in response to the impact magnitude after the foot strikes the ground because voluntary muscle activity has a latency of 170 ms (Enoka, 1988). Typical impact magnitudes during running are about 1.66 ± 0.16 BW for speeds around 3.2 $m \cdot s^{-1}$ (Challis, 2001). This is comparable to the impact magnitudes in the present study of 1.40 ± 0.27 BW at 2.1 ± 0.3 $m \cdot s^{-1}$ for the nonweighted running condition.

Simpson, Bates, and McCaw (1988) studied the effects of added weight to the ankles on GRF while running. They reported that nonweighted running produced an average impact magnitude of 18.24 N/kg, which is greater than the impact magnitudes observed in the present study (11.92 N/kg). During running with added weight, impact magnitude was 13.44 N/kg. This magnitude is slightly lower than Simpson et al. (1988) that reported an average weighted impact magnitude of 17.2 N/kg. The difference in F1 magnitudes between the two studies could be explained by the different placement of the added weight on the body. Simpson et al. (1988) placed the weights on the ankles, while in the present study the weight was placed on the trunk. It appears from Simpson et al. that the more distally on the leg the weight is placed the higher the impact magnitudes. While F1 magnitudes are different in the two studies, the absolute increase in impact (N/kg) between the weighted and nonweighted conditions is about the same (1.52 N/kg for the present study, and 1.04 N/kg for Simpson et al., 1988). When adding weight to the ankles while running, Simpson et al (1988) concluded that F1 magnitudes were not different when running with and without added weight, which was also observed in the present study ($p<0.05$).

Newton's second law of motion states that the acceleration of an object is proportional to the applied force and inversely proportional to the object's mass. Or, in other words, force is equal to the product of mass and acceleration of the object ($F=ma$).

During running, the ground reaction force (GRF) is the product of the mass of the runner and acceleration of the center of mass. Running style affects center of mass acceleration; therefore, applying the concept of F=ma to running, if acceleration changes, and mass stays the same, the resultant force will change. Since acceleration is the change in velocity over a certain period of time, changing running style, such as changing SL or SF, will affect the velocity prior to ground contact. If velocity changes, acceleration during the impact phase will also change. This means that if mass remains the same, a change in SL or SF will produce changes in the GRF. Using F=ma, the following hypotheses can be stated: 1) if F1 was observed to increase during running with added weight, then running style (SF or SL) did not change; 2) if F1 remained the same during running with added weight, then it would seem that running style (SF or SL) changed.

An example of how running style can change impact magnitudes is displayed in a study examining the relationship between different running surfaces and impact magnitudes (Dixon, Collop, & Batt, 2000). Dixon et al. (2000) studied the effect of surface stiffness (i.e. soft or hard) on impact magnitudes. Six subjects performed running trials over three surfaces, 1) asphalt, 2) rubber-modified asphalt, and 3) acrylic sports surface. Dixon et al. (2000) reported no differences between the impact magnitudes between the three conditions. The maintenance of impact peaks across running surfaces was explained by the kinematic running changes that occurred during the different running surfaces. In other words, running style changed. Since running style changed, the acceleration changed, and therefore, the force magnitudes were maintained across conditions (F=ma).

In addition to changes in SL and SF, and running surfaces, changes in impact magnitudes have also been associated with changes in running speeds (Hamill, Bates,

Knutzen, & Sawhill, 1983). Hamill et al. (1983) reported that as running speed increases, F1 magnitudes increase as well. They attributed this to the increases in SL that are associated with changes in running speeds.

In the present study, SL and SF were not experimentally manipulated from preferred selection during Experiment 1, and running surface and running speed were the same across conditions. Changes in running surfaces, speed, SF, and SL could have caused unwanted changes in impact magnitudes between the weighted and nonweighted conditions. Although these conditions did not change between conditions, an increase in impact magnitude was still expected from Newton's second law of motion (F=ma). A 30% increase in mass was expected to result in a 30% increase in force, if 'a' remained the same. However, F1 did not increase with 30% added weight, but stayed the same magnitude as in the PSF_{NW} condition. This seems to indicate that subjects adopted a new running style while wearing the weight, changing 'a', which resulted in impact peak magnitudes to be maintained within a certain range of normal nonweighted running.

Active Peak Force (F2)

The active peak force represents the maximum force in the vertical direction and occurs at about midstance (Nigg et al., 1995). F1 occurs between the first 25-50 ms of stance time. Since it takes the muscle 170 ms to begin activation, the body therefore, has enough time to adjust running style if necessary to affect F2 magnitude. The major contributor to the magnitude of F2 is the acceleration of the trunk. Therefore, if mass remains constant, and acceleration of the trunk changes during midstance, such as by changes in running style, the magnitude of the force should change also.

Active peak forces have been reported as high as 2.80 ± 0.12 BW during running at 3.3 $m \cdot s^{-1}$ (Challis, 2001) which is comparable to the results of the present study, that

observed F2 magnitudes of 2.17 ± 0.24 BW during running at 2.1 m·sec^{-1}. Simpson et al. (1988) reported that average F2 magnitude while running with added ankle weight was 24.74 N/kg (about 2.4 BW). This is similar to the 24.93 N/kg F2 magnitudes observed during weighted running in the present study. The present study also observed that average F2 magnitude was 14.8% greater during PSF_W compared to PSF_{NW} condition.

The present study observed that F2 magnitudes increased during the PSF_W compared to the PSF_{NW} running condition, however, the increases were not 30%; the average increase was about 15% from the PSF_{NW} to the PSF_W condition. Table 8 illustrates individual F2 values as a percent change form PSF_{NW} condition.

Average Vertical Force (F_{zavg})

Average vertical force was used as a descriptor of the general force trend between running conditions. Simpson et al. (1988) reported F_{zavg} values of about 14.4 N/kg during nonweighted running. The present study observed F_{zavg} values of 12.04 N/kg during the nonweighted running condition. Simpson et al. (1988) also reported an F_{zavg} of 14.38 N/kg while running with added ankle weight. The present study observed F_{zavg} as 13.61 N/kg during the weighted running condition. F_{zavg} increased while running with 30% added trunk weight, however, the increase was not 30%. F_{zavg} was 11.8% greater during weighted running compared to no added weight running. Table 9 displays all subjects average forces as a percentage of the PSF_{NW}. The results of experiment 1 seem to indicate that while running with added weight, the body does not regulate F2 and F_{zavg} magnitudes as strictly as F1 magnitudes. This is indicated by the maintenance of F1 magnitudes, while there was an increase in F2 and F_{zavg} magnitudes during weighted running. Although F2 and F_{zavg} increased during weighted running, it was not a 30%

Table 8. Individual subject percent change in F2 magnitudes from PSF_{NW} (no added weight) to PSF_{W} conditions (30% added weight).

Subject	Percent change From PSF_{NW}
1	15.1%
2	15.9%
3	15.0%
4	20.3%
5	8.7%
6	19.3%
7	12.8%
8	17.6%
9	11.6%
10	11.3%
Average	14.8%
Standard deviation	±0.04

Table 9. Individual subject percent change in F_{zavg} from PSF_{NW} to PSF_W conditions.

Subject	Percent change from PSF_{NW}
1	15.9%
2	10.8%
3	16.4%
4	17.2%
5	11.1%
6	12.6%
7	4.0%
8	12.6%
9	10.3%
10	6.9%
Average	11.8%
Standard deviation	±0.04

increase as would be expected from Newton's second law of motion. This indicates that the body adapted somehow during weighted running, in order for the F2 and F_{zavg} magnitudes to increase 14% and 11.8% respectively, and not 30%. Therefore, it seems that the body optimizes mainly on F1 and not F2 or F_{zavg}, however there is some regulation of both F2 and F_{zavg}.

Experiment 1 Conclusions

Force data indicates adjustments are being made to maintain F1 magnitudes. A possible mechanism used to maintain F1 magnitudes between nonweighted and weighted conditions could be changes in ST and leg stiffness.

Stance Time and Leg Stiffness Mechanism

Stance time (ST) is the amount of time the foot is in contact with the ground. Martin (1985) reported ST to be 0.27 seconds during nonweighted running at 3.3 $m \cdot s^{-1}$. The present study observed average ST to be 0.34 seconds during nonweighted running at 2.1 $m \cdot s^{-1}$. The difference in ST between the two studies could be explained by the difference in running speed. Hamill et al. (1983), as well as Cavanagh and LaFortune (1980) reported that ST was negatively correlated with running speed. Specifically, as running speed increased, stance time decreased. No studies known to the author have investigated the effect of added trunk weight on ST while running. In the present study, ST was 11.0 ± 0.01% greater during the PSF_W condition compared to the PSF_{NW} condition.

Factors that may influence ST are leg stiffness and stride frequency (SF). Farley and Gonzales (1996) analyzed leg stiffness while running at different stride frequencies. The authors concluded that as stride frequency increases, leg stiffness increases during running at a set speed. In addition, Farley and Gonzales (1996) reported that while running, as SF is increased while running, ST will decrease. Therefore, they concluded there was a negative correlation with ST and leg stiffness; as SF increased there was an increase in leg stiffness and a concurrent decrease in ST. Another study supporting the conclusion that as ST increases, leg stiffness decreases, was McMahon et al. (1987). They studied a running style called "Groucho running," which was characterized as having extreme knee flexion during the stance phase of running. It was reported that as leg stiffness decreased, stance time increased, which is in agreement with Farley and Gonzales (1996).

Since leg stiffness was not quantified in the present study. ST was used as an indicator of changes in leg stiffness while running with added weight on the overground conditions in experiment 1. While ST was used as an indicator of leg stiffness in the present study. kinematics is the only way to determine the exact degree of change at each joint involved in response to the added weight. Kinematics was not recorded in this study and therefore. is a limitation of the present study.

In experiment 1 it was observed that F1 did not increase. and F2 increased during the PSF_W conditions compared to the PSF_{NW} condition. This observation is evidence that the subjects optimized on impact (F1) during experiment one. The present study did not investigate the exact underlying mechanism of how individuals optimized on impact. however Heise and Marin (1998) listed several contributing factors influencing the magnitude of impact during running. These factors included the impact velocity. contact area. joint angles at initial impact. motion of the segment centers of masses particularly the foot. muscle preactivation. surface stiffness and leg stiffness (Heise & Martin. 1998).

The present study observed that ST was significantly different ($p<0.05$) between the PSF_{NW} (0.337 ± 0.050 s) and PSF_W (0.380 ± 0.057 s) conditions. All subjects increased ST during the added weight condition. with the average increase being $11.0\pm0.01\%$ (table 10). Since average stance time increased in the PSF_W condition. this suggests that the subjects were running with a more compliant running style while running with the added weight. An increase in running compliancy suggests that the subjects were trying to decrease impact magnitudes. therefore. optimizing on impact.

The results of experiment 1 in the present study indicate that running style changed while running with 30% added body weight. Since running style seemed to change from the preferred running style. it seems logical to think that VO_2 would

increase as well. Experiment 2 investigated the effects 30% added body weight had on VO_2.

Experiment 2

Oxygen Consumption (VO_2) – PSF_{NW} and PSF_W

Running intensity is associated with oxygen consumption: the higher the intensity, the greater the oxygen consumption. Relative oxygen consumption ($ml \cdot kg^{-1}min^{-1}$) can be calculated and predicted using the ACSM metabolic equations, which includes the factors of speed and grade to predict VO_2 . Using ACSM's metabolic equation ($VO_2 = 3.5 + [0.2 \times speed] + [0.9 \times speed \times grade]$), it was expected that while running at 2.1 ± 0.30 $m \cdot s^{-1}$ relative VO_2 would be equal to 28.82 ± 3.69 $ml \cdot kg^{-1}min^{-1}$. This is comparable to the results of the present study, which observed VO_2 to be 29.6 ± 4.6 $ml \cdot kg^{-1}min^{-1}$ while running at 2.1 ± 0.3 $m \cdot s^{-1}$. There are no studies known to

Table 10. Individual percent change in stance time from PSF_{NW} to PSF_W conditions.

Subject	Percent change From PSF_{NW}
1	11.8%
2	9.7%
3	8.1%
4	9.4%
5	12.6%
6	10.4%
7	20.3%
8	5.7%
9	7.7%
10	14.4%
Average	11.0%
Standard deviation	±0.01

the author that has measured VO_2 while wearing 30% added trunk weight to compare the present study's data.

The effect added mass has on VO_2 during running seems to be dependent on the amount of mass added and where the mass is placed. Thorstensson (1986) studied the effects 10% added trunk weight had on VO_2 in male adults and 10-year-old boys. For adults, it was reported that VO_2 ($L \cdot min^{-1}$) increased 8.7% while running with 10% added weight. For children an increase in VO_2 ($L \cdot min^{-1}$) of 6.9% was reported by Thorstensson (1986). Martin (1985) studied the changes in VO_2 ($ml \cdot kg^{-1} min^{-1}$) with added weight to the thigh and ankle. Martin (1985) concluded that increases in the weight placed on the thigh or ankle produced an increasing linear trend in oxygen consumption. Furthermore, the more distal the weight was placed the greater the effect on oxygen consumption. Cureton et al. (1978) studied the effects of 5%-15% added trunk weight on VO_2 ($ml \cdot kg^{-1} min^{-1}$). They concluded that VO_2 ($ml \cdot kg^{-1} min^{-1}$ and $l \cdot min^{-1}$) increased linearly from 5% to 15% added weight.

In the present study, it was observed that VO_2 ($ml \cdot kg^{-1} min^{-1}$) increased 22% when running with 30% added trunk weight. This is close to the prediction of the linear equation developed by Epstein, Stroschein, and Pandolf (1987) to determine the oxygen cost of running with added loads. According to their equation, VO_2 should increase in proportion to the added weight (i.e., 30%). Using the equation published by Epstein et al. (1987), VO_2 was equated to be 38.48 $ml \cdot kg^{-1} min^{-1}$ with a 30% increase in weight. This is a 30% increase from the observed unweighted VO_2 ($ml \cdot kg^{-1} min^{-1}$). The present study observed the weighted VO_2 to be 36.21 ± 6.81 $ml \cdot kg^{-1} min^{-1}$ which is very close to the VO_2 predicted by Epstein et al. Since individuals usually run in a manner that optimizes VO_2 (Cavanagh & Williams, 1982), and because VO_2 increased as expected from the

nonweighted to weighted conditions, it seems that VO_2 was optimized during weighted running. However, VO_2 optimization cannot be determined by comparing nonweighted and weighted running only. Evidence for optimization can be provided by the observance and manipulation of SF and SL, which is the purpose of the second half of experiment 2.

VO_2 during +10% PSF_W and –10% PSF_W

In the present study, it was observed that VO_2 was sensitive to decreases in SF while running with 30% added body weight. Specifically, VO_2 during the -10% PSF_W condition was about 8% higher than the VO_2 during the PSF_W conditions, while there was no difference ($p>0.05$) between the +10% PSF_W and PSF_W conditions (Figure 9). These results are similar to the findings of Martín and Morgan (1992) and Hogberg (1952) who reported that it was more costly to run at a stride frequency less than preferred than running with a greater than preferred stride frequency.

According to Cavanagh and Williams (1982), VO_2 is minimized at the PSF, however, there is a relatively flat portion of the curve around the PSF. This flat portion around the PSF region indicates that small changes in SF may not have a major effect on oxygen uptake. Cavanagh and Williams (1982) reported that with a change in SL of 4.2 cm or 4.5% of leg length, there was only a 0.2 $ml \cdot kg^{-1} min^{-1}$ change in VO_2. From the results of Cavanagh and Williams (1982), the present study expected the PSF_{NW} to result in minimal oxygen consumption. In the present study, running with 30% added weight (PSF_W) increased SF 3.4% from the PSF_{NW} condition, indicating that running style changed slightly between the no weight and weighted conditions. Even though the SF between the weighted and nonweighted conditions were significantly different ($p<0.05$), the percent change between the weighted and nonweighted conditions was only 3.4%.

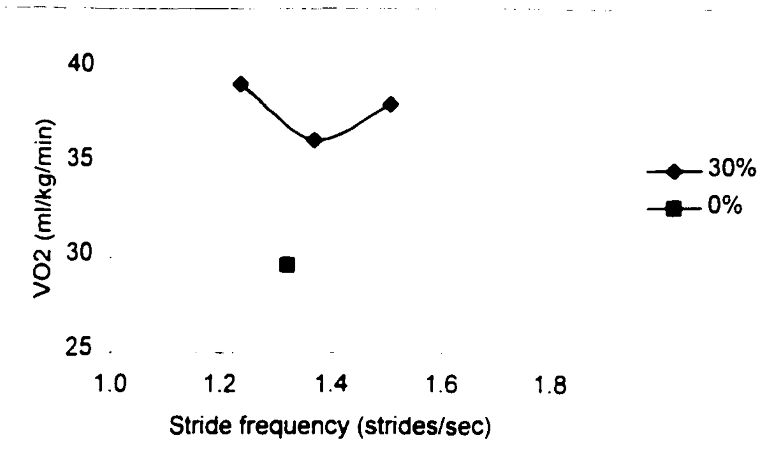


Figure 9. Group mean VO_2 during PSF_{NW} and PSF_W, $-10\%PSF_W$, and $+10\%PSF_W$ conditions.

This indicates that the subjects were running with a SF that would be on the flat portion of the original nonweighted VO_2-SF curve that minimized VO_2. This observation suggests that despite the small changes in SF, the subjects seem to be optimizing on VO_2 while running with 30% added weight in the present study.

Experiment 2 Conclusion

VO_2 during weighted running seems to be minimized despite a small increase in SF. VO_2 seems to be optimized during weighted running.

Experiment 1 and 2 Combined

Stride Frequency

Stride frequency is an influencing factor on both VO_2 and impact magnitude. As SF increases from PSF, VO_2 increases (Cavanagh & Williams, 1982), and impact decreases (Derrick, Hamill, & Caldwell, 1998). In the present study, stride frequency increased an average of 3.4% between the PSF_{NW} and PSF_W conditions ($p<0.05$). Thorstensson (1986) studied the effects of 10% added trunk weight on the SF of 10-year-old boys and male adults. He observed that SF had a tendency to increase with added weight. Davies (1980) also studied the effects of 10% added trunk weight on children's SF. He concluded that 10% added trunk weight did not change SF in children while running. While no known studies have observed the effects 30% added body weight has on SF, the results of the present study, that SF increased with added body weight, is supported by Thorstensson (1986) which concluded that SF had a tendency to increase with addition of extra body weight.

In addition to increasing VO_2, increasing SF is a possible mechanism used to decrease impact while running (Derrick, 1998). In the present study, impact did not

increase during the 30% added weight condition compared to the nonweighted condition, however SF increased. This is in agreement with Derrick (1998) that reported a decrease (or, in this case, maintenance) in F1 magnitudes with an increase in SF.

The present study found only a slight difference in SF between PSF_{NW} and PSF_W, indicating that running style did not change dramatically, and quite possibly VO_2 was minimized. However, the results of the present study also indicate that impact (F1) did not change between PSF_{NW} and PSF_W, indicating that impact was also optimized. One possible strategy the body may use to decrease impact and minimize VO_2 is to slightly increase stride frequency (Derrick et al., 1998). The results of this study demonstrate that SF did slightly increase from the no added weight condition to the weighted condition. Figure 9 (p. 49) illustrates the increase in SF from the nonweighted to the weighted conditions, and also the increase in VO_2, which occurred with deviations from PSF_W. These observations suggest that subtle increases in SF from the PSF_{NW} to the PSF_W condition was a mechanism used to optimize impact; however, the PSF_W was still within the flat portion of the nonweighted VO_2-SF curve, which minimizes VO_2.

As stated previously, SF, leg stiffness, and ST all affect F1 magnitudes while running; however, VO_2 is affected by these factors as well (Heise & Martin, 1998). The findings of the current study that ST increased from PSF_{NW} to PSF_W seem to support Heise and Martin (1998) that concluded runners who exhibited a low vertical stiffness (decreased leg stiffness) tended to be less economical than runners who ran with a higher vertical stiffness. This may explain the increase in VO_2 from PSF_{NW} to PSF_W. McMahon et al. (1987) also studied leg stiffness during groucho running and found that the deeper the groucho running, the greater the increase in VO_2 (up to a 50% increase). McMahon et al. (1987) suggested that the largest contributor to this increase in VO_2 may be the

increased force required during eccentric contraction of the knee extensors during the knee flexion in the stance phase.

During experiment one, only impact forces were quantified, while during experiment two, SF and VO_2 changes were quantified. It is not known if the accommodation strategy to running with added weight is different during overground and treadmill running. Elliott & Blanksby (1976) compared overground running characteristics to treadmill running characteristics. They reported that during slow jogging speeds there were no significant differences recorded in SF, SL, swing time, or stance phase comparing overground and treadmill running. While this might be true for normal running conditions, there were some confounding results between the overground and treadmill running conditions while wearing the added weight. During overground running ST was increased during the 30% added weight condition compared to the no added weight condition. Since ST is inversely related to SF (Farley & Gonzales, 1996), it could be concluded that during experiment one SF decreased. However, during treadmill running, SF was quantified and was observed to increase while running with added weight compared to the no added weight condition.

One possible explanation of how both ST and SF increased could be the order in which each accommodation mechanism was implemented. Increasing ST, or leg compliancy, could be the first 'answer' in response to increased impact, and this mechanism could be employed at lighter added loads. However, increasing leg compliancy is not an endless adaptation. Perhaps, at a certain degree of leg compliancy, the body cannot run more compliantly and therefore, has to implement another mechanism in order to decrease impact, such as increasing SF. While SF is a mechanism that can be used to decrease impact, just like lower extremity compliancy, SF is not an

endless adaptation. There may be a point when the load reaches a level that elicits a SF so high that the body cannot physically run. Perhaps, it is at this point, when both mechanisms, ST and SF, are maximized, and therefore, impact must increase. In the present study it was observed that both ST and SF increased during running with 30% added body weight. One possible explanation for this observation is that 30% added body weight might have elicited a maximum change in ST and therefore, SF increased in order to keep impact optimized. The observation that both ST and SF increased with 30% added body weight could possibly be that 30% added body was not enough weight to elicit an extremely high SF (maximum SF), and therefore, did not cause an increase in impact.

Another possible explanation of why the overground running resulted in a seemingly decreased SF while wearing 30% added weight, is the relationship between ST, flight time, and SF. Stride frequency is the sum of stance time and flight time. Therefore, if ST increased, as during the weighted overground running, flight time could have decreased which could have resulted in the same SF or a decreased SF compared to the nonweighted overground running. Since kinematics were not analyzed for this experiment, it is difficult to draw conclusions about the actual mechanisms behind the minimization of F1 magnitudes.

The results of experiment 1 and 2 in the present study indicate that the body is able to optimize on both VO_2 and impact. Evidence supporting this is the increase in SF from PSF_{NW} to PSF_W. Increases in SF decrease impact magnitudes, however, increases in SF potentially result in increases in VO_2. While VO_2 did increase from the nonweighted to the weighted conditions, VO_2 was minimized in the PSF_W condition, as

indicated by the increases in VO_2 at the ±10% PSF_W. Therefore, it seems that with 30% added body weight, the subjects optimized on both VO_2 and impact.

Individual Responses

While the group mean for impact peaks (F1) did not have a significant difference between the PSF_{NW} and PSF_W conditions, there was a wide range of individual responses to the added weight. Subject 1 did not display any impact peaks while running with 30% added weight, which would suggest that the subject perceived the weight (and potential increase in impact) as having the possible cause for injury and therefore, adopted a running strategy as to eliminate the F1 impact all together. Subject 7 did not display any impact peaks for either the PSF_{NW} and PSF_W conditions. This is usually seen when the individual is a "toe runner", however, that was not the case for this subject. One possible explanation for not displaying F1 peaks in PSF_{NW} condition is that the subject was not used to running on concrete flooring, and perceived this stiff surface as having the potential for injury, thereby changing the running style in order to eliminate the impact peaks.

Another possible explanation of why no F1 magnitudes were seen in subjects 1 and 7 is the slow running speeds. For the present study, running speed was self-selected, and in order for the subjects to complete all the conditions, the subjects chose very slow running speeds. The running speeds chosen for subjects 1 and 7 were 1.8 and 1.9 $m \cdot s^{-1}$ respectively. These speeds could be considered walking speeds, and therefore, have a double support phase. A typical walking GRF curve does not have an impact peak, and therefore, could be an explanation of why subjects 1 and 7 displayed no impact peaks. Subject 10 displayed impact peaks, however, they were reduced by 33.3% when wearing

the added weight. This observation suggests that subject 10 perceived the weight as an extremely high risk for injury and therefore, decreased the impact even more than the normal running (0% added weight). Table 11 displays the percent change for F1 magnitudes from PSF_{NW} and PSF_W conditions for all subjects.

Table 11 illustrates the wide range of responses between subjects while running with added weight. This wide range of adaptive responses was also observed by Simpson et al. (1988), who studied the effects of added ankle weight on GRFs during running. They concluded that subjects used a wide range of strategies to accommodate to the added weight. The two extreme strategies were the purely Newtonian strategy, which increased impact with added weight, and the accommodation strategy, which decreased impact with added weight. These were the extreme strategies, however, with numerous combinations of Newtonian and accommodation strategies were observed while running with weight on the ankles (Simpson et al., 1988). The group mean for VO_2 was different between the −10% PSF_W and PSF_W conditions, and not different between the +10% PSF_W and PSF_W, however, most subjects performed different than the group average. Figure 10 illustrates the percent change in VO_2 for the ±10% PSF_W conditions. Table 12 displays the percent change in VO_2 for the ±10% when compared to the PSF_W condition. Both figure 10 and table 12 illustrate the wide range of VO_2 responses for running with the added weight. Eight of the ten subjects increased VO_2 during the ±10% PSF_W compared to the PSF_W condition. In contrast, subject 2 had a lower VO_2 during ±10% PSF_W conditions compared to PSF_W (see appendix I). Subject 4 also had a lower VO_2 during the −10% PSF_W condition compared to the PSF_W condition (see appendix I). This may be evidence that subject 4 was running at a point on the VO_2-SF curve that did not minimize VO_2, since VO_2 was not minimized at the PSF_W. This observation suggests that

Table 11. Individual percent change in F1 magnitudes from PSF_{NW} and PSF_W conditions

Subject	Percent change from PSF_{NW}
1	———
2	-5.4%
3	12.0%
4	10.7%
5	-4.5%
6	-2.4%
7	———
8	-4.0%
9	12.3%
10	-33.3%
Average	-1.8%
Standard deviation	±0.05

it was more economical to run at −10% PSF_W, than at the PSF_W for subject 4. Even though it was more economical to run at −10% PSF_W, this subject choose to run at a higher SF than optimal. Since impact decreases with increasing SF (Derrick, 1998), subject 4 was running at a SF that did not optimize VO_2, possibly trying to decrease impact. Subject 2 displayed an unusual decrease in VO_2 during the +10% PSF_W condition (see appendix I). When analyzing the VO_2 data for all subjects excluding subject 2, there was a significant increase between the average VO_2 during the +10% PSF_W condition and the VO_2 during the PSF_W condition (see appendix II). This observation adds support to the previous conclusion that VO_2 was minimized during the PSF_W condition.

The variety of responses to added weight during running supports that the exact mechanism of accommodation, or lack of accommodation, is dependent on many individual factors. Considering the majority of subjects followed similar patterns, a group approach to understanding accommodation seems appropriate. However, since some individuals responded differently than the group, research on individual accommodations to added weight is needed.

Conclusions

The results of this study indicate that 30% added weight is sufficient weight to induce a change in running style that optimizes on impact. While impact is optimized while running with 30% added weight, VO_2 is also minimized. Therefore, null hypotheses 7, 9, 10, 11, and 12 are rejected. There were significant differences between PSF_{NW} and PSF_W condition for VO_2, F2, F_{zavg}, SF, and ST. There was no difference between F1 magnitudes in the PSF_{NW} and PSF_W conditions; therefore null hypothesis 8 is accepted.

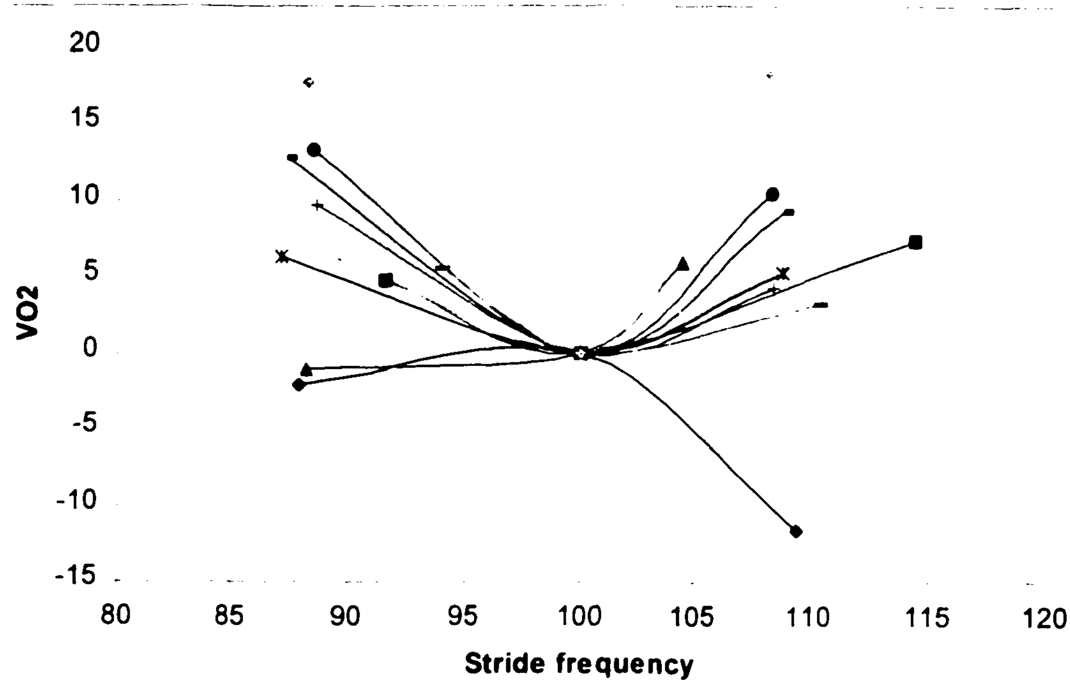


Figure 10. All subjects VO_2 percent change from PSF_W. VO_2 at PSF_W was set equal to zero; PSF_W was set equal to 100. Each set of identical markers illustrates VO_2 for a subject.

Table 12. Percent change of VO_2 for the ± 10% PSF_W from the PSF_W condition.

Subject	% change VO_2 -10% PSF_W	% change VO_2 +10% PSF_W
1	17.77	18.3
2	-2.1	-11.6
3	4.8	7.4
4	-1.1	6.0
5	6.4	5.3
6	13.2	2.8
7	13.4	10.5
8	9.7	4.2
9	12.9	9.4
10	5.6	3.3
Average	8.1	5.6
Standard deviation	±6.4	±7.6

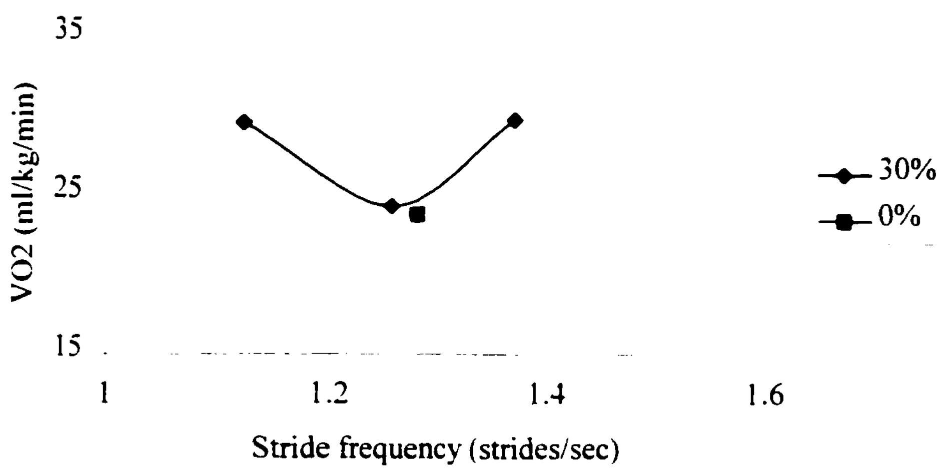
APPENDIX I

INDIVIDUAL SUBJECT DATA

Subject 1

Subject	1
BW	128.30
BW (newtons)	570.32
added Wt	38.50
total BW	166.80
total BW (newtons)	741.46
height (in.)	64.00
Age	34.00
Body fat	18.79

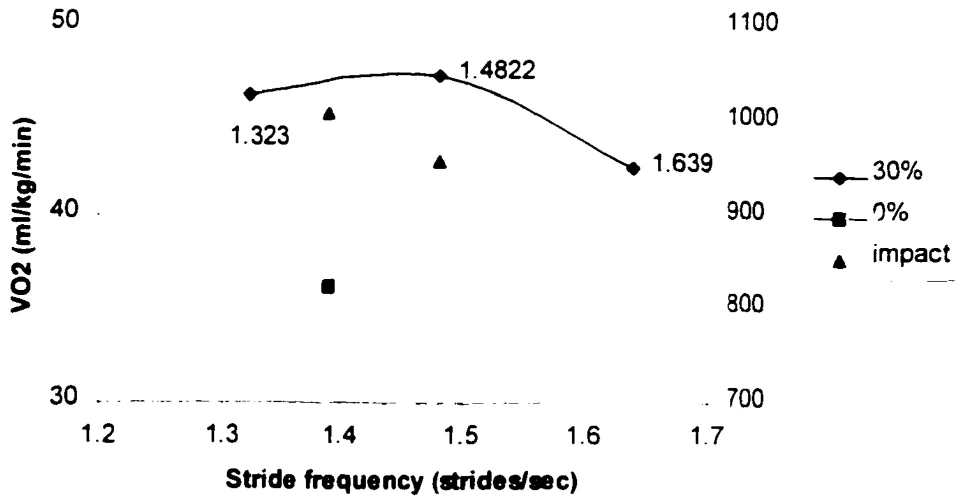
	0% added wt PSF_{NW}	30% added weight -10% PSF_W	30% added weight PSF_W	30% added weight +10% PSF_W
SF	1.28	1.125	1.257	1.37
VO2	23.78571	29.58571	24.32857	29.77143
F1	582.4627		0	
F2	965.5947		1137.567	
Fz avg	566.5067		673.8052	
ST	0.437863		0.496163	



Subject 2

BW	128.4
BW (newtons)	570.76
added Wt	38.52
total BW	166.92
total BW (newtons)	741.99
height (in.)	66
age	23
Body fat	21.00

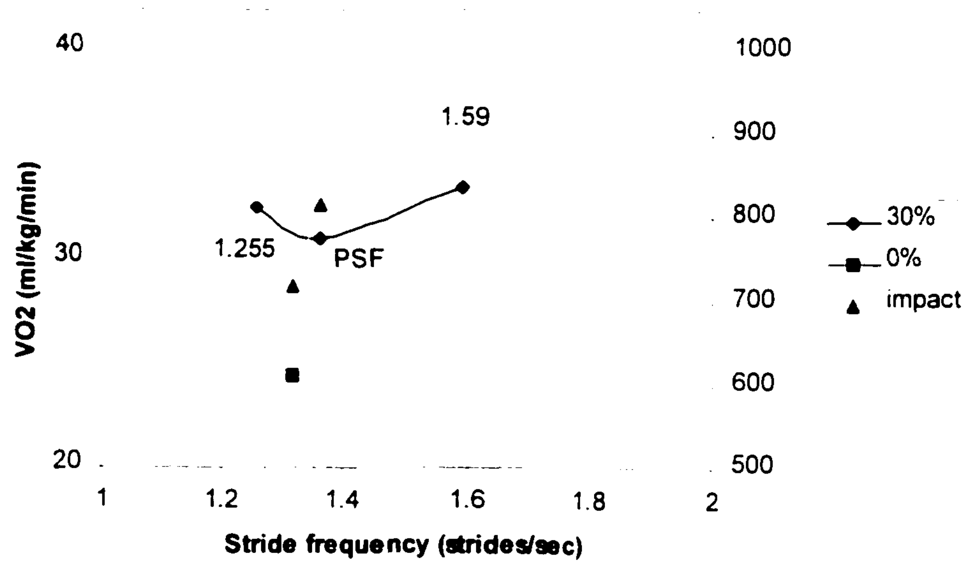
	0% added wt PSF_{NW}	30% added weight -10% PSF_W	30% added weight PSF_W	30% added weight +10% PSF_W
SF	1.39	1.323	1.482	1.64
VO2	36.23	46.3857	47.36	42.44
F1	1008.56		957.18	
F2	1361.35		1618.59	
Fz avg	813.43		911.99	
ST	0.27		0.30	



Subject 3

Subject	3
BW	145
BW (newtons)	644.554232
added Wt	43.5
total BW	188.5
total BW (newtons)	837.9205016
height (in.)	68
Age	21
Body fat	30.41

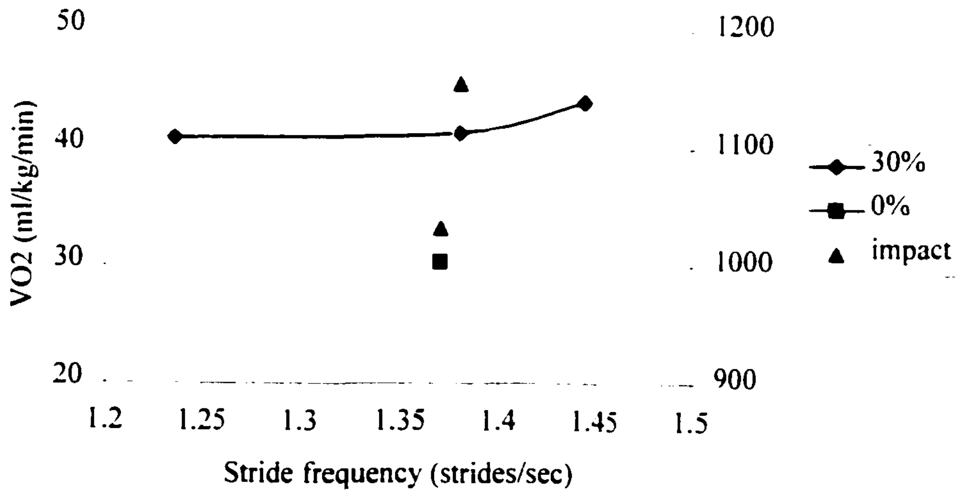
	0% added wt PSF_{NW}	30% added wt -10% PSF_W	30% added wt PSF_w	30% added wt +10%PSF_W
VO2	24.44286	32.55714	30.98571	33.47143
SF	1.315	1.255	1.36	1.59
F1	717.3434		815.6548	
F2	1386.63		1630.574	
Fz avg	680.0336		813.1572	
ST	0.3853		0.419025	



Subject 4

subject	4
BW	169.70
BW (newtons)	754.35
added Wt	50.91
total BW	220.61
total BW (newtons)	980.66
height (in.)	68.00
age	26.00
Body fat	29.86

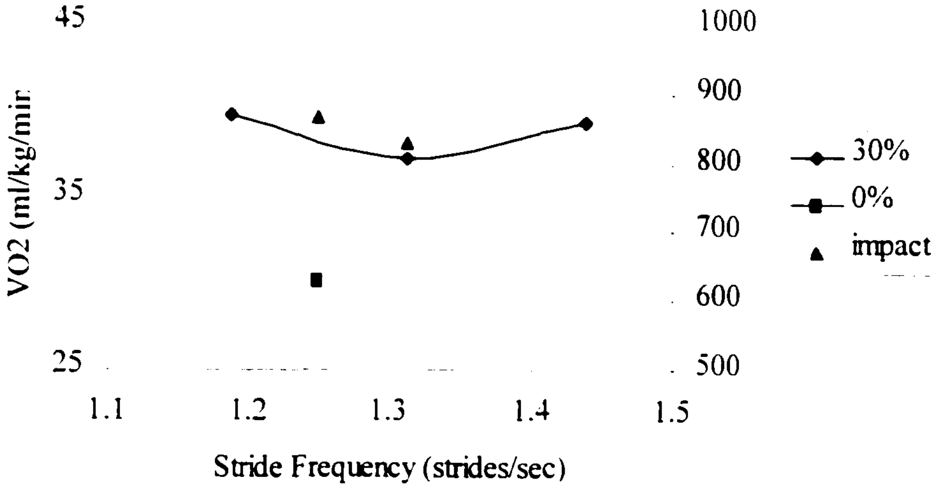
	0% added wt PSF_{NW}	30% added wt -10% PSF_W	30% added wt PSF_W	30% added wt +10%PSF_W
SF	1.37	1.23	1.38	1.44
VO2	30.34	40.87	41.31	43.94
ST	0.35		0.38	
F1	1031.90		1155.29	
F2	1428.52		1791.83	
Fz avg	808.29		976.13	



Subject 5

subject	5
BW	148.7
BW (newtons)	661.0014779
added Wt	44.6
total BW	193.3
total BW (newtons)	859.2574693
height (in.)	70
age	20
Body fat	29.89

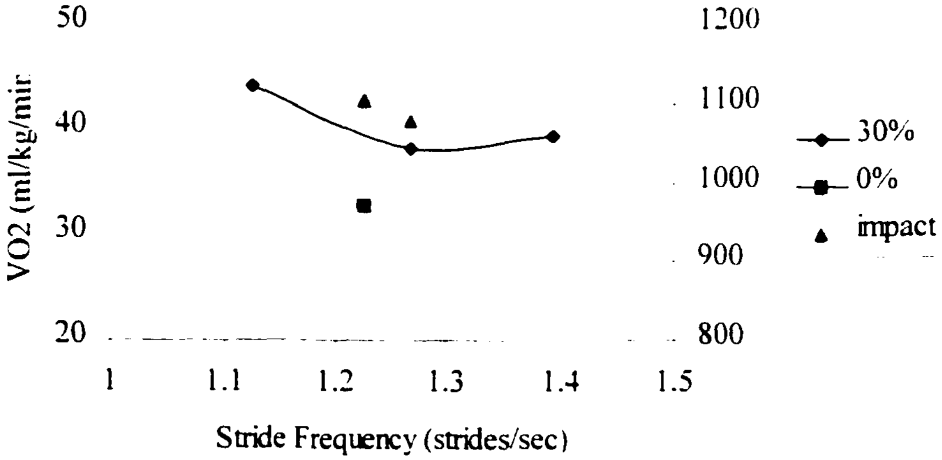
	0% added wt PSF_{NW}	30% added wt -10% PSF_W	30% added wt PSF_w	30% added wt +10%PSF_W
SF	1.25	1.19	1.31	1.44
VO2	30.12857	39.87143	37.32857	39.4
F1	866.4493		829.2449	
F2	1489.368		1631.024	
Fz avg	888.5762		999.7254	
ST	0.341763		0.391	



Subject 6

Subject	6
BW	147.40
BW (newtons)	655.22
added Wt	44.20
total BW	191.60
total BW (newtons)	851.70
height (in.)	65.00
Age	30.00
Body fat	21.57

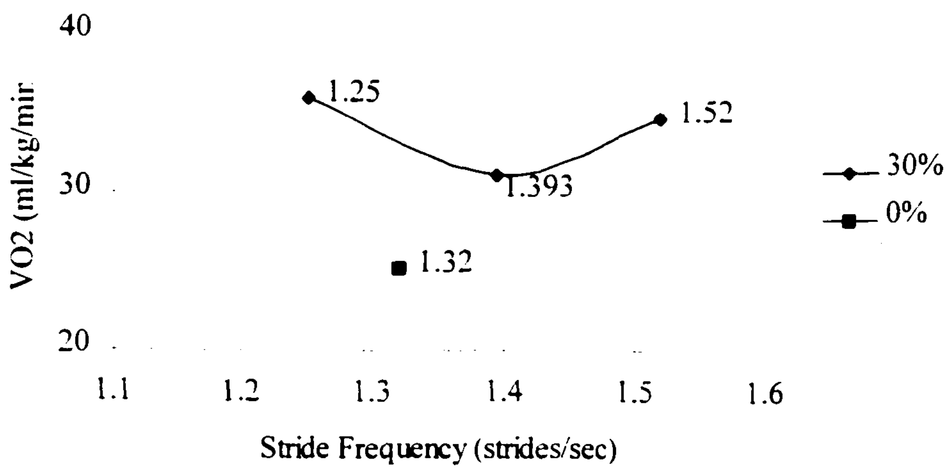
	0% added wt PSF_{NW}	30% added wt -10% PSF_W	30% added wt PSF_w	30% added wt +10%PSF_W
SF	1.227	1.125	1.269	1.392
VO2	32.82857	44.11429	38.3	39.4
ST	0.303575		0.338925	
F1	1103.851		1078.35	
F2	1588.852		1969.848	
Fz avg	917.8162		1050.08	



Subject 7

subject	7
BW	157.40
BW (newtons)	699.67
added Wt	47.22
total BW	204.62
total BW (newtons)	909.58
height (in.)	65.00
age	21.00
Body fat	26.30

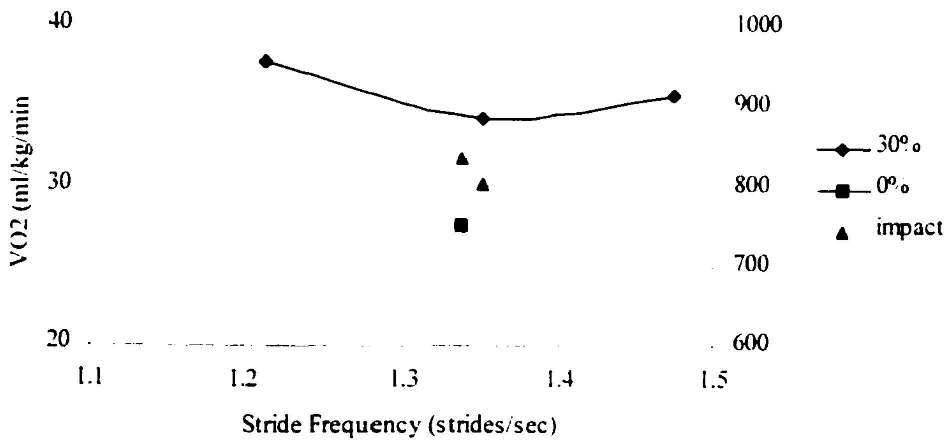
	0% added wt PSF_{NW}	30% added wt -10% PSF_W	30% added wt PSF_w	30% added wt +10%PSF_W
SF	1.32	1.25	1.393	1.52
VO2	25.14286	35.94286	31.12857	34.77143
ST	0.329625		0.413563	
F1				
F2	1533.727		1759.21	
Fz avg	854.5915		890.4073	



Subject 8

subject	8
BW	136.20
BW (newtons)	605.44
added Wt	40.86
total BW	177.06
total BW (newtons)	787.07
height (in.)	67.00
age	33.00
Body fat	23.83

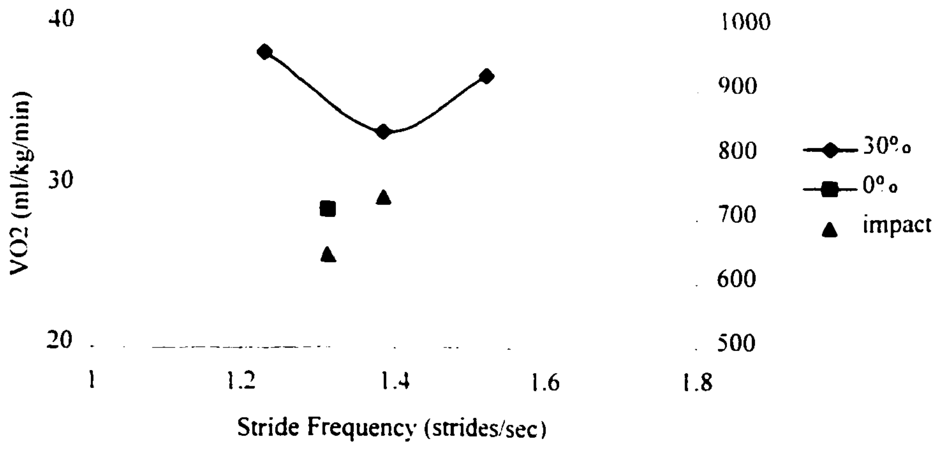
	0% added wt PSF_{NW}	30% added wt -10% PSF_W	30% added wt PSF_W	30% added wt +10%PSF_W
SF	1.337	1.213	1.35	1.475
VO2	27.6	37.9	34.22857	35.72857
ST	0.347475		0.36855	
F1	835.8432		804.059	
F2	1249.845		1516.866	
Fz avg	711.2689		813.7465	



Subject 9

Subject	9
BW	146.00
BW (newtons)	649.00
added Wt	43.80
total BW	189.80
total BW (newtons)	843.70
height (in.)	65.00
Age	21.00
Body fat	28.67

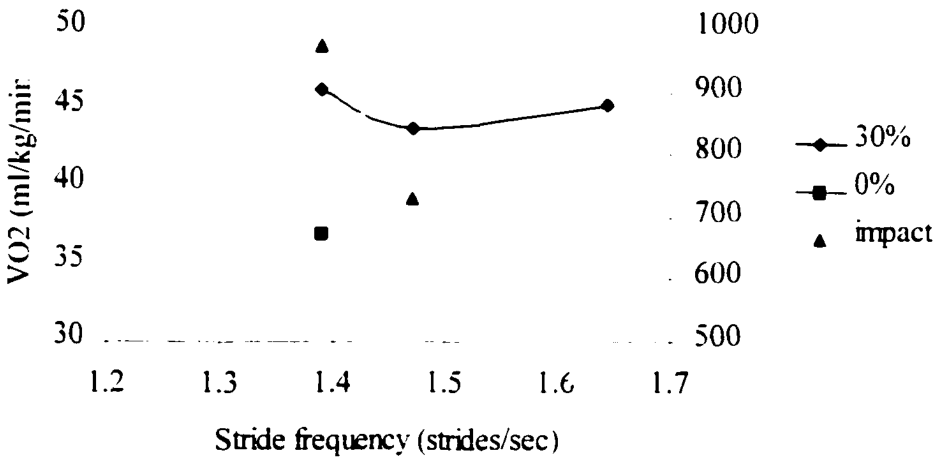
	0% added wt PSF_{NW}	30% added wt -10% PSF_W	30% added wt PSF_w	30% added wt +10%PSF_W
SF	1.313	1.23	1.384	1.52
VO2	28.6	38.45714	33.5	36.97143
ST	0.341763		0.3703	
F1	644.6804		735.4387	
F2	1435.727		1624.936	
Fz avg	795.6063		887.0485	



Subject 10

subject	10
BW	141.80
BW (newtons)	630.33
added Wt	42.54
total BW	184.34
total BW (newtons)	819.43
height (in.)	63.00
age	24.00
Body fat	26.10

	0% added wt PSF_{NW}	30% added wt -10% PSF_W	30% added wt PSF_w	30% added wt +10%PSF_W
SF	1.39	1.39	1.47	1.645
VO2	36.9	46.23	43.66	45.14
ST	0.268238		0.313375	
F1	976.2237		732.1378	
F2	1542.138		1739.318	
Fzavg	871.526		936.0637	



APPENDIX II

STATISTICAL TESTS

F1

Test excluding subjects 1 and 7

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.396	1.375
Variance	0.071	0.046
Observations	8.000	8.000
Pearson Correlation	0.733	
Hypothesized Mean Difference	0.000	
Df	7.000	
t Stat	0.329	
P(T<=t) one-tail	0.376	
t Critical one-tail	1.895	
P(T<=t) two-tail	0.752	
t Critical two-tail	2.365	

F2

Test including subjects 1 and 7

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	2.172	2.549
Variance	0.057	0.076
Observations	10.000	10.000
Pearson Correlation	0.919	
Hypothesized Mean Difference	0.000	
Df	9.000	
t Stat	-10.856	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.262	

Test excluding subjects 1 and 7

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	2.229	2.623
Variance	0.037	0.048
Observations	8.000	8.000
Pearson Correlation	0.841	
Hypothesized Mean Difference	0.000	
df	7.000	
t Stat	-9.424	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.895	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.365	

F_{zavg}

Test including subjects 1 and 7

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.229	1.392
Variance	0.024	0.022
Observations	10.000	10.000
Pearson Correlation	0.943	
Hypothesized Mean Difference	0.000	
df	9.000	
t Stat	-9.861	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.262	

Test excluding subjects 1 and 7

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	1.260	1.433
Variance	0.022	0.018
Observations	8.000	8.000
Pearson Correlation	0.968	
Hypothesized Mean Difference	0.000	
df	7.000	
t Stat	-12.660	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.895	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.365	

Stance time

Test including subjects 1 and 7

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.337	0.380
Variance	0.003	0.003
Observations	10.000	10.000
Pearson Correlation	0.948	
Hypothesized Mean Difference	0.000	
df	9.000	
t Stat	-7.253	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.833	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.262	

Test excluding subjects 1 and 7

t-Test: Paired Two Sample for Means

	Variable 1	*Variable 2*
Mean	0.326	0.361
Variance	0.002	0.002
Observations	8.000	8.000
Pearson Correlation	0.975	
Hypothesized Mean Difference	0.000	
df	7.000	
t Stat	-10.823	
P(T<=t) one-tail	0.000	
t Critical one-tail	1.895	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.365	

VO_2

ANOVA

Source	Sum of Squares	df	Mean Square	F value	Significance
VO_2	554.188	3	184.729	64.229	.000
Error	77.655	27	2.876		

Tukey's Test

Condition	Mean Difference	Critical Difference	Significant
PSF_{NW} vs PSF_W	6.46	3.83	Yes
PSF_{NW} vs –10% PSF_W	10.01	3.83	Yes
PSF_{NW} vs +10% PSF_W	8.78	3.83	Yes
PSF_W vs –10% PSF_W	2.979	3.83	Yes
PSF_W vs +10% PSF_W	1.89	3.83	No

ANOVA – excluding subject 2

Source	Sum of Squares	df	Mean Square	F value	Significance
VO_2	504.281	3	168.094	79.168	.000
Error	50.958	24	2.123		

Tukey's test

Condition	Mean Difference	Critical Difference	Significant
PSF_{NW} vs PSF_W	6.11	1.87	Yes
PSF_{NW} vs –10% PSF_W	9.53	1.87	Yes
PSF_{NW} vs +10% PSF_W	8.74	1.87	Yes
PSF_W vs –10% PSF_W	3.42	1.87	Yes
PSF_W vs +10% PSF_W	2.63	1.87	Yes

ANOVA – excluding subject 1, 2, 7

Source	Sum of Squares	df	Mean Square	F value	Significance
VO_2	421.748	3	140.583	81.652	.000
Error	30.991	24	1.722		

Tukey's test

Condition	Mean Difference	Critical Difference	Significant
PSF_{NW} vs PSF_W	6.92	1.934	Yes
PSF_{NW} vs –10% PSF_W	9.88	1.934	Yes
PSF_{NW} vs +10% PSF_W	9.025	1.934	Yes
PSF_W vs –10% PSF_W	2.96	1.934	Yes
PSF_W vs +10% PSF_W	2.105	1.934	Yes

APPENDIX III

SUBJECTS DESCRIPTIVE DATA

SUBJECT	BW	BW (NEWTONS)	ADDED WT	TOTAL BW	TOTAL BW (NEWTONS)	HEIGHT (IN.)	AGE	BODY FAT
1	128.30	570.32	38.50	166.80	741.46	64.00	34	18.79
2	128.40	570.76	38.52	166.92	741.99	66.00	23	21.00
3	145.00	644.55	43.50	188.50	837.92	68.00	21	30.41
4	169.70	754.35	50.91	220.61	980.66	68.00	26	29.86
5	148.70	661.00	44.60	193.30	859.26	70.00	20	29.89
6	147.40	655.22	44.20	191.60	851.70	65.00	30	21.57
7	157.40	699.67	47.22	204.62	909.58	65.00	21	28.67
8	136.20	605.44	40.86	177.06	787.07	67.00	33	23.83
9	146.00	649.00	43.80	189.80	843.70	65.00	21	28.67
10	141.80	630.33	42.54	184.34	819.43	63.00	24	26.10
Mean	144.89	644.07	43.47	188.36	837.28	66.10	25.30	25.88
SD	±12.59	±55.96	±3.77	±16.36	±72.74	±2.13	±5.25	±4.28

APPENDIX IV

INFORMED CONSENT

UNLV

Department of Kinesiology
Exercise Physiology and Biomechanics Lab

Subject Informed Consent Form for Participation

We appreciate your interest in participating in this research study. Note that your participation is entirely voluntary and that you are free to withdraw yourself as a subject at any time. It is expected that you are currently physically active and are between the ages of 18 and 45 and are free from any physical impairment or injury. If you feel you do not meet these qualifications, please let the researcher know.

The purpose of this study is to investigate the energy cost and ground reaction forces with added body weight. You will be asked to run on a treadmill at a comfortable running speed, 0% grade, while wearing a weighted vest equaling 0%, and 30% of your body weight. There will be 4 running conditions lasting 7 minutes total for each condition on the treadmill. They are as follows:

0% added weight, running at your normal stride rate
30% added weight, running at your normal stride rate
30% added weight, running at +10% your normal stride rate
30% added weight running at –10% your normal stride rate

During the conditions of ±10% your normal stride rate you will be asked to run to the beat of a metronome which will be set at ±10% of your normal stride rate. You will be fitted with a sterilized, reusable mouthpiece similar to a snorkel during all run conditions in order to measure energy cost. Ground reaction force data will be collected after the first two run conditions by stepping off the treadmill and running across a force platform that is situated flush with the floor of the lab. Each testing session will last approximately 45-60 minutes.

This research study does not require you to engage in any activity that is unusual or unfamiliar to you. Please be aware, however, that lower extremity joint and muscle injury is always possible in any locomotion activity. You will thus be encouraged to actively warm-up prior to each testing session, such that you feel physically prepared to perform the running activity.

You may stop the data collection at any time. A principal investigator will be present at each data collection session to answer any inquiries you have concerning the procedures. The names of all subjects will be held in strict confidence and will not be revealed in any publication or reports resulting from this study. The informed consents will be collected by a laboratory assistant, and stored in a locked file cabinet in the Exercise Physiology laboratory (SIRC 102) at UNLV for at least three years. Those individuals who choose not to participate will be excused from the study.

All references to subjects will be made solely on the basis of a subject number assigned for the study. The code sheet relating subject names to subject numbers will be maintained in a confidential file.

It is hoped that you benefit from being a participant. You are welcome to make an appointment to review the results of the study, and if you wish to have a copy of the results of the study, please let us know. Once you have read this informed consent form, and all of you questions have been answered, you are requested to sign and date the form below. Your signature indicates that you have read and understand the procedures, have had all of you questions answered, understand the limited risks involved in participating, agree to voluntarily participate in all phases of the study as described above, and understand that you may withdraw from the study at any time. If questions arise after the data collection, an investigator may be reached at 895-4494 or 895-1582. If you have any questions regarding the rights of research subjects please contact the UNLV Office for the Protection of Research Subjects at (702) 895-2794. Thank you for participating in this project.

Subject name: ________________________________ Date: __________

Subject signature: ____________________________ Date: __________

Witness: ____________________________________ Date: __________

APPENDIX V

OFFICE OF THE PROTECTION OF RESEARCH

SUBJECTS APPROVAL LETTER

UNLV

DATE: February 23, 2001

TO: Wendy Hibner
Kinesiology
M/S 3034

FROM: Dr. Jack Young
Chair, Biomedical Sciences Committee
UNLV Institutional Review Board

RE: Status of Human Subject Protocol Entitled:
"Optimization Characteristics While Running With Added Trunk Weight"

OPRS# 504s0201-228

This memorandum is official notification that the Biomedical Sciences Committee of the Institutional Review Board approved the protocol for the project listed above and work on the project may proceed. This approval is effective **February 20, 2001** and will continue for a period of one year.

Should the use of human subjects described in this protocol continue beyond a year from the approval date, it will be necessary to request an extension.

If you have any questions or require any assistance, please contact the Office for the Protection of Research Subjects at 895-2794.

cc: OPRS File

Office for the Protection of Research Subjects
4505 Maryland Parkway • Box 451046 • Las Vegas, Nevada 89154-1046
(702) 895-2794 • FAX (702) 895-4242

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