BIOMECHANICAL EFFICIENCY AND METABOLIC ECONOMY: VIBRAM FIVE FINGERS VERSUS CONVENTIONAL RUNNING SHOES

by

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ABSTRACT

Minimalist running shoes like Vibram Five Fingers have flooded the market and shoe companies claim that they may improve biomechanical efficiency and metabolic economy when compared with conventional running shoes. PURPOSE: To test claims made by Vibram that running in their Five Finger (VS) shoes improves biomechanical efficiency and metabolic economy when compared to running in conventional shoes (CS). METHODS: Ten trained runners (18-35 yrs) completed a randomized, continuous treadmill running protocol in each footwear type. VO_2 measurements were continuously collected during three submaximal stages. Each stage was five minutes in duration (6, 7.5 & 9 mi/hr) with three-minute walking recoveries between each stage in order to ensure steady state VO_2. Saggital plane kinematic data were collected at 210 Hz using a high-speed video camera. Kinematic data were analyzed using KA PRO 7 kinematic analysis software. VO_2 data from CS and VS shoe conditions were compared using repeated measures ANOVA. Differences between spatiotemporal and kinematic variables across conditions were analyzed using paired t-tests. RESULTS: The metabolic energy consumption (VO_2) in VS was lower than in CS at 6 mph (33.3 vs. 33.8 ml•kg^{-1}min^{-1}), 7.5 mph (40.0 vs. 41.2 ml•kg^{-1}min^{-1}), and 9 mph (48.3 vs. 49.6 ml•kg^{-1}min^{-1}) but the results were not significant ($p<0.93$). Average delta efficiency in the VS condition was slightly higher (14.5%) than that of the CS (14.2%) condition but the difference was not significant ($p<0.89$). CONCLUSION: Results showed small, non-significant improvements in efficiency and economy in the VS shoe condition when compared with the CS condition. Results showed that only three out of ten subjects transitioned from RFS to non-RFS, and this stability in foot strike across conditions may explain the relatively small magnitude of improvement in efficiency and economy. Two out of three of minimalist-experienced subjects transitioned from RFS to non-RFS but only one out of four minimalist-inexperienced subjects transitioned. These results indicate that barefoot or minimalist training may be more critical than footwear choice in improving efficiency and economy in running.

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Chapter One: Introduction to the Study

A debate exists among runners and footwear experts whether conventional cushioned, stabilized running shoes or new minimalist-style running shoes designed with less cushioning and support are most effective for biomechanical efficiency and metabolic economy (Perl, Daoud, & Lieberman, 2012; Squadrone & Gallozi, 2009; Jenkins & Cauthon, 2011).

Conventional running shoes (CS) are designed with a thick heel cushion that promotes a rear foot strike (RFS) pattern adopted by approximately 75% of runners (Hasegawa, Yamauchi, & Kraemer, 2007), and some research suggests that running with a RFS is biomechanically inefficient and metabolically uneconomical (Lieberman et al., 2010; Divert et al., 2008). Early advocates of CS described human feet as being evolutionarily unsuccessful (Grabiner, 1989). Shoe manufacturers and medical professionals contended that feet were fragile and needed support, cushion, and motion control in order to withstand the harshness of running (Jenkins & Cauthon, 2011).

Conventional running shoes are marketed on the premise that they reduce injury and optimize performance, but research shows such advertising may be deceptive, and that lower-cost shoes may have better cushioning and lower plantar pressures than expensive shoes of the same brand (Clinghan, Arnold, Drew, Cochrane, & Abboud, 2007). Furthermore, a systematic review of literature on injury and performance revealed that the prescription of conventional running shoes with elevated heel, cushioning and pronation-control customized to the individual's foot type is not evidence-based (Richards, Magin, & Callister, 2009).

Barefoot and minimalist running shoe proponents argue that running barefoot and in minimalist shoes strengthens the feet, improves proprioceptive feedback and forces runners to adopt more natural, efficient stride mechanics involving a forefoot (FFS) or midfoot strike (MFS) pattern, (Lieberman et al., 2010; Robbins & Hanna 1986; Squadrone & Gallozi, 2009). According to Dr. Ivo Waerlop (2010) of the Vibram Biomechanics Advisory Board, "Running in Five Fingers improves agility, strength, and equilibrium, plus it delivers sensory feedback that allows runners to make immediate corrections to their form. This greatly improves running efficiency" (para 3). However, these sweeping claims are unsubstantiated by well-controlled research studies with large samples representative of the recreational athletes to whom these minimalist shoes are being marketed (Perl, et al., 2012).

Theoretical Framework

Aspects that determine successful distance running performance are mainly maximal aerobic power (VO_2 max), lactate threshold, biomechanical efficiency and metabolic economy. Since VO_2 max is usually similar among high-level runners, other aspects may explain success in performance conditions. Runners with a higher lactate threshold than their competitors will have a performance advantage. In the same way, runners who have superior biomechanical efficiency and metabolic economy will have lower energy expenditures for a given speed and will have an edge over their competition (McCardle, Katch, & Katch, 2010).

Metabolic economy is a commonly used performance measure defined as a runner's oxygen consumption (VO_2) for a given running speed (Sherman & Jackson, 1998). Both biomechanical efficiency and metabolic economy incorporate the estimation of energy expenditure (VO_2). However, the calculation of biomechanical efficiency represents the ratio of mechanical work accomplished to VO_2 consumed (Kaneko, 1990).

Newtonian physics is the theoretical basis for the calculation of mechanical work and biomechanical efficiency (Winter, 1979). Thermodynamics is the theoretic basis for estimation of caloric equivalence of VO_2 (Gaessar & Brooks, 1975). The calculation of both biomechanical efficiency and metabolic economy require the measurement of VO_2 in order to estimate the energy input during exercise.

Bramble and Lieberman (2004) theorized that humans evolved adaptations that enable exceptional endurance running, particularly barefoot running. Among these adaptations, the elastic properties of the Achilles tendon and the plantar fascia of foot arch improve biomechanical efficiency and metabolic economy through the process of absorbing and returning kinetic energy though a mechanical model know as the mass-spring mechanism (Bramble & Lieberman, 2004). This theoretically efficient barefoot-style of running is what drives the marketing and popularity of running in minimalist and Vibram Five Finger footwear.

Conceptual Framework

A thorough review of the literature at the time of the present study revealed little published research specifically comparing efficiency differences of treadmill running between VS and CS. However, in a study comparing treadmill running in CS versus running in diver's socks, researchers found a significant increase in efficiency in the diver sock condition (Divert et al., 2007). In a study comparing VS, barefoot and CS running, researchers found a significant improvement in economy in the VS condition when compared to CS (Squadrone & Gallozi, 2009).

Based on the theory of the mass-spring mechanism of the Achilles tendon and foot arch, running barefoot or in VS may be more efficient than running in CS (Bramble & Lieberman, 2004; Alexander, 1991; Ker, Bennett, Bibby, Kester, & Alexander, 1987). Studies have shown that sensory feedback from the foot is blocked by thick cushioning CS but running barefoot or in VS improves sensory feedback. This improved sensory feedback may drive kinematic changes in running form that reduce ground reaction force and improve efficiency and economy (Robbins & Hanna, 1986; Squadrone & Gallozi, 2009).

Similar to previous research, the present study compares efficiency, economy and lower extremity kinematic differences in the saggital plane, such as stride length and foot strike pattern, between VS and CS conditions. However, unlike previous studies (Squadrone & Gallozzi, 2009; Divert et al., 2008) with treadmill tests at one moderate running speed, the present study tested runners in three stages of increasing submaximal speed (6.0, 7.5 and 9.0 MPH). This protocol addresses limitations in previous research because it includes a range of submaximal running speeds that variably challenge both biomechanical and metabolic systems. In addition, this challenging protocol is more representative of real-life performance conditions and designed for competitive athletes.

If running in VS can reduce ground reaction force and improve kinematics, efficiency and economy, then it may be of monumental importance to runners. All running footwear design is theory-driven and this study seeks to test whether or not quantifiable differences in efficiency and economy exist between running in CS and VS.

Statement of the Problem

Several variables are relevant to distance running performance, such as aerobic power (VO_2 max), lactate threshold, neuromuscular fitness, psychological skill, metabolic economy and biomechanical efficiency. Given two distance runners with matched ability in all aspects of performance except biomechanical efficiency, the more efficient runner has an advantage (Kaneko, 1990; Bramble & Lieberman, 2004; Lieberman et al., 2010). If minimalist shoes can improve a runner's efficiency by changing strike pattern from RFS to FFS or MFS, then they have the potential to improve running performance. Research has shown that with a FFS or MFS pattern, the elastic properties of the Achilles tendon and foot arch can potentially return 35% and 17% of energy, respectively (Alexander, 1991; Ker et al., 1987). Additionally, the kinematic change to FFS pattern with barefoot or minimalist shoes eliminates the impact transient associated with RFS pattern in CS and produces three times less impact force (Lieberman et al., 2010).

Significance of the Problem

The United States is in the midst of the biggest running boom in decades with an estimated 13 million race finishes nationwide and the largest increase (10%) in race finishes ever recorded by Running USA during 2010. Running shoe sales in 2011 reached an estimated $2.33 billion, a 1% increase over 2010, but conventional running shoe sales actually dropped 18% while minimalist shoe sales increased 283%, representing $1.7 billion (Newman, 2011).

With the popularity of running races and minimalist shoes both increasing, it behooves runners to educate themselves about their safety risks and performance benefits. The minimalist running movement has recently become popular and has the potential to revolutionize the running shoe industry and the sport of distance running (Jenkins & Cauthon, 2011).

Statement of Purpose

The purpose of this study is to test the claim by the Vibram Company that runners wearing Vibram Five Finger shoes (VS) make immediate improvements to their running form and run more efficiently than runners wearing conventional running shoes (CS). Specifically, this study seeks to addresses the research question, "Does running in VS improve biomechanical efficiency and metabolic economy compared to running in CS?"

Hypotheses

The two hypotheses tested in this study are as follows:

1. Running in VS is biomechanically more efficient than running in CS due to alterations in running kinematics and kinetics.
2. Running in VS is metabolically more economical than running in CS due to reduced shoe mass and altered running biomechanics.

Chapter Two: Review of Literature

Minimalist footwear may have a significant impact on running performance, and this may be of great interest to all runners. This review of literature covers evidence supporting the evolutionary basis of barefoot running and biomechanical efficiency. Additionally, this review covers different factors attributable to footwear choice that may affect running performance, efficiency and economy. Lastly, this review compares minimalist and conventional footwear from biomechanical efficiency and metabolic economy perspectives.

The Evolutionary Basis of Running Efficiency and Economy

In contrast to other animal species, over 2 million years of evolution has uniquely adapted humans for long-term endurance running. Persistence hunting is the evolutionary explanation for human adaptation to endurance running. The theory is that early hominids adapted, both physiologically and anatomically, the endurance to run down their prey to the point of exhaustion without using weapons (Bramble & Lieberman, 2004). Other anthropological research supports this, noting the theoretical development of characteristic human morphology as adaptations for saving energy over great distances (Preuschoft, 2004).

Additionally, an Outside Magazine article (Bethea, 2011) reviewed a group of nine elite marathon runners in New Mexico who tested the persistence hunting theory by attempting to run down the fastest land animal in the Western Hemisphere (up to 62 mi/hr), the pronghorn. Although the runners did not kill the pronghorn, they were able to tire and separate one from the herd and get close enough to deem that the theory of persistence hunting as possible (Bethea, 2011).

The theory of persistence hunting is controversial. One recent study (Steudel-Numbers, & Wall-Schleffer, 2009) found that the use of persistence hunting methods to catch prey at any running speed, even at the most optimal, would be energetically more costly than at optimal walking speed. This suggests that neither extinct nor existing human populations are as flexible in the chosen speeds of persistence hunting pursuits as other researchers like Bramble and Lieberman (2004) have theorized. Variations in the efficiency of human locomotion appear to be similar to those of terrestrial quadrupeds and therefore humans do not have an efficiency advantage over their prey (Steudel et al., 2009).

Results from another study (Cunningham, Schilling, Anders, & Carrier, 2010) compared cost of transport in digitgrade (FFS) and plantigrade (RFS) locomotion and showed that humans evolved to be economical at walking but not running. However, this study lacked statistical strength (N=6) and did not control for training level of participants (Cunningham et al., 2010). Furthermore, evidence supporting the evolution of endurance *running* as opposed to walking includes the adaptations of the large erector spinae muscles, and a greatly enlarged gluteus maximus. The large size of the gluteus makes it among the most distinctive of all human features and it is strongly recruited in all running speeds but *not* in walking on level surfaces (Bramble & Lieberman, 2004).

Aside from the persistence hunting theory, Lieberman (2012) argues that humans have been running distances for millions of years on hard and rough surfaces and mostly barefoot or with minimal foot covering. In addition to adaptations to skeletal strength, stabilization and thermoregulation, another important early human adaptation was in energetics. One part of this adaption is a biomechanical model known as a mass-spring mechanism. Muscle and tendon tissues have elastic properties that capture, store and return kinetic energy. Anatomically, two structures that are critical to the conservation of energy during barefoot running are the Achilles tendon and the longitudinal arch of the foot (Bramble & Lieberman, 2004).

In barefoot and VS running, the mass-spring mechanism is theoretically better exploited than in CS running. The stride length is shorter in barefoot running, which necessitates a midfoot strike (MFS) or forefoot strike (FFS) and a more compliant landing with the force translated to the longitudinal foot arch as well as Achilles tendon and triceps surae muscles of the calf. Energy is efficiently stored and released like a spring, helping to reduce ground reaction forces at the point of foot strike. In contrast, theoretically less efficient CS runners tend to RFS, increase ground reaction force (GRF), lengthen stride, and lose compliance with a more extended leg with strike forces being attenuated to a greater degree by the joints and lesser so by foot arch, Achilles tendon and muscles (Lieberman et al., 2010). (See later section on mass-spring mechanism and efficiency.)

Theoretically, feedback from the feet is the mechanism that drives barefoot-style running mechanics (Lieberman et al., 2010; Robbins & Hanna 1986; Squadrone & Gallozi, 2009). Vibram researchers even claim that these adaptive changes to running form are *immediate* (Waerlop, 2010). However, conclusions from some research on habitual RFS runners shows that some were successful and others were unsuccessful in their attempts to adapt a reduced-force barefoot strike (Dixon, Collop, & Batt, 2005).

Whereas early human beings adapted to be exceptional at endurance running for the purposes of survival, modern humans engage in endurance running as a sport and a recreational activity. In contrast to barefoot runners who FFS or MFS, approximately 75% of CS endurance runners today tend to RFS (Hasegawa, H., Yamauchi, T., & Kraemer, W., 2007). Runners who RFS cope with the impact transient of the ground reaction force, an abrupt collision force of 1.5 to 3 times body weight. However, FFS and MFS running produces no impact transient and GRF three times lower than RFS running (Lieberman et al., 2010).

Endurance running is common to both modern and prehistoric humans, but the difference is that our hominid ancestors ran barefoot or minimally shod for the purpose of survival. If millions of years of evolution selected for successful barefoot running in humans, then maybe the way we run today in conventional shoes is a mismatch to that evolutionary selection, and as such, is problematic (Lieberman, 2012).

A Comparison of Conventional and Minimalist Footwear

Recreational and competitive athletes commonly ran either barefoot or in minimal shoes until the 1970's when CS were invented with heel cushioning, stiff sole and arch support. It is logical to assume that the human body must be well adapted to barefoot running, perhaps making shoes unnecessary or even potentially injurious to runners. Evolutionarily speaking, barefoot running is just as natural to humans as barefoot walking, but in our modern culture it is considered trendy and dangerous (Lieberman, 2012).

Early advocates of CS believed that human feet were not evolutionarily successful (Grabiner, 1989); shoe manufacturers and medical professionals contended that feet were fragile and needed support, cushion, and motion control in order to withstand the harshness of running (Jenkins & Cauthon, 2011). Purported benefits of CS are injury prevention and performance but research shows that CS advertising may be deceptive, and that less expensive shoes may have better cushioning and induce lower plantar pressures than more expensive shoes of the same brand (Clinghan et al., 2007). Furthermore, a systematic review of literature revealed that conventional shoes with elevated heel, cushioning and pronation-control customized to the individual's foot type for prevention of injury and performance are not evidence-based (Richards et al., 2009).

Conventional running shoes limit proprioception, facilitate non-barefoot running style, and hypothetically cause foot weakness and inflexibility (Lieberman, 2012). Conventional shoe running relies on cushioning and support against heel strike; in contrast, minimalist-shoe running relies on changing technique into a more natural, barefoot running style. Barefoot running's characteristic foot strike patterns, stride lengths and stride rates, physiological adaptations, and running cost improvements support the hypothesis of injury prevention and improved performance (Lieberman, 2012).

Although running in minimalist shoes is not exactly the same as barefoot running, shoes like Vibram Five Fingers (VS) have been developed for runners seeking the theoretical benefits of barefoot running with the addition of light foot protection (Squadrone & Gallozzi, 2009). VS are minimalist since there are no cushioning or stability features and their construction consists of rubber outsole, microfiber foot bed and fabric or neoprene upper. The shoes look distinctive because of the five slots that allow independent toe movement. They are approximately half the weight of most conventional running shoes because they lack a midsole (Minimalist running footwear, 2011).

Biomechanical Efficiency

In human running, the skeletal muscles exert forces through the locomotor system, acting internally on the body and externally on the ground to move the body's center of gravity forward. The energetics of running can be analyzed by calculating biomechanical efficiency. As cited by Kaneko (1990), Hill (1927) defined mechanical efficiency for exercising humans as "mechanical work done per unit energy expended" (p. 57).

Three major methods are employed for calculating mechanical work in running: one method involves measuring energy changes on the body's center of gravity, a second method involves segmental energy analysis derived from kinematics, and a third method involves calculating changes in segmental power derived from joint moments and forces (Kaneko, 1990; Williams, 2008).

In 1979, Winter proposed a definition of mechanical work that includes both the external work and the internal work done by the limbs themselves. The internal work derives from a biomechanical analysis that accounts for all components of potential and kinetic energy, all energy exchanges within and between segments, and both positive and negative work completed by the muscles. Winter applied his method in a study of eight subjects walking at different walking speeds. He estimated the internal work per stride as calculated from the sum of segment energies and compared it to the same calculation on the body's center of mass energy (Winter, 1979).

Winter's (1979) method allows for a separation of total positive and negative work components and his definition of efficiency of human movement includes the utilizing of the internal mechanical work plus external work in the numerator.

Additionally, this method allows for the calculation of efficiency in level running without an external load. Lastly, Winter's (1979) results revealed 16-40% error associated with efficiency estimated from the body's center of mass energy (Cavagna & Margaria, 1966) when compared to his total energy transfer approach.

A major assumption that was not stated in Cavagna and Margaria's (1966) approach is that the energy of the body's center of mass represents the sum of all segment energies. The reciprocal movements are not accounted for and the force plate does not record any measure of segment rotational kinetic energy (Winter, 1979).

Similarly, a running efficiency study by Harris, DeBeliso, and Adams (2003) used three different calculations for estimating both internal and external work and power during running. One approach considered no energy transfer (Norman, Sharratt, Pezzack, & Noble, 1976), a second approach considered that no energy transferred between body segments (Pierrynowski, Winter, & Norman, 1980) and a third approach considered total energy transfer (Winter, 1979). For all three approaches, the basic method involved determination of each segment's instantaneous potential energy, translational kinetic energy, and rotational kinetic energy throughout a running cycle (Harris et al., 2003).

Each algorithm varied in the manner in which segmental changes in energy level summed and were exclusive in the degree of energy transfer permitted. One limitation of this study's methodology was its failure to consider the contribution of elastic energy storage and reuse. Researchers have suggested that stored energy in the elastic components of soft tissues contributes to positive external work generation without additional metabolic cost (Assmusen & Bonde-Petersen, 1974). As a result, elastic energy could add to changes in positive energy level. The work performed might be an overestimate due to the inability to account for the influence of elastic energy. Other research explains limitations of the kinematic-based method for calculating mechanical work and power (van Ingen Schenau & Cavanagh, 1990; Williams & Cavanagh, 1987).

Donovan and Brooks (1977) pioneered using the delta efficiency calculation as the most accurate method of describing the relationship between caloric output and the external work rate in cycling and running and they concluded it to be the most appropriate method of calculating efficiency (Donovan & Brooks, 1977). A similar, more recent study compared the delta efficiency of running and cycling by applying two different modes of external work: treadmill inclination and horizontal impeding forces (Bijker, De Groot & Hollander, 2001a). The researchers derived the delta efficiency of running by calculating mechanical work in watts, defined as Pmech = (m)(v)(sin θ), the metabolic energy input in watts, defined as Pmet = (4.94•RER+16.04)/60•VO_2 and the percentage delta efficiency in watts, defined as Δ E= (Δ Pmech/Δ Pmet) x 100 (Bijker et al, 2001a).

Although 5 kilocalories is widely used in research as caloric equivalent per liter of oxygen, it is an oversimplification since it does not consider the individual energy contributions of carbohydrate and fat. The RER is the ratio of CO_2 produced to O_2 consumed and its value varies depending on the dominant substrate utilization. Simply put, different amounts of oxygen are required for the complete oxidization of the carbon and hydrogen atoms in a substrate molecule to the end-products CO_2 and H_2O: RER (RQ) is 1.0 for carbohydrate, 0.70 for fat, and 0.82 for protein (American College of Sports Medicine, 1998). Therefore, it is necessary to consider RER when estimating aerobic power (Pmet) with specific consideration given to the simultaneous contributions of fat and carbohydrate during steady state exercise (Garby & Astrup, 1987). Garby and Astrup's method for calculating aerobic power and delta efficiency has been validated in numerous studies (Bijker et al., 2001a; Bijker, de Groot, & Hollander, 2001b; Hettinga et al., 2007).

Although methods have advanced, there remain methodological problems with the calculation of mechanical power during running. Challenges include quantifying the energy transfer between segments and net muscle forces, defining the source of mechanical power, understanding the effect of muscles that cross multiple joints, and the contribution of the stretch-shortening cycle to mechanical work (van Ingen-Schenau, Bobbert & de Haan, 1997). Until these problems get resolved, the usefulness of the measures of mechanical work and efficiency will be limited (Williams, 2008).

The mass-spring mechanism. Human legs possess long spring-like tendons connected to short muscle fascicles that can efficiently produce force and are estimated to save approximately fifty percent of the energetic cost of running. In contrast to CS running with RFS impact where the translational kinetic energy is lost in the collision, in barefoot running a FFS impact occurs towards the front of the foot and the ankle dorsiflexes under control of the triceps surae muscles and Achilles tendon. The ground reaction force (GRF) rotates the foot around the ankle, which transfers part of the lower limb's translational kinetic energy into rotational kinetic energy (Lieberman et al., 2010).

If running in VS shoes mimics barefoot running and better exploits the mass-spring mechanisms by encouraging FFS, then the energy savings may improve efficiency. During running, tendons and ligaments in the legs store elastic strain energy during the braking segment of the support phase, and then release the energy by recoiling during the propulsive phase. The most important of these springs is the Achilles tendon, which connects the heel with the major plantar flexors of the foot and can produce as much as 35% energy return (Alexander, 1991). The plantar fascia of the longitudinal arch of the foot is another important structure that acts as a spring returning roughly 17% of the energy generated during stance phase (Ker et al., 1987). By contrast, another footwear study (Webb, Saris, Schofflen, van Ingen Schenau, & Ten Hoor, 1988) found repetitive deformation of CS with each stride and a resulting energy loss that could have been saved in the barefoot running condition.

Stride length and stride frequency. Among the ways of describing running style, two common spatiotemporal descriptors are stride length (SL) and stride frequency (SF). Research shows that runners naturally adopt a running style with a SF and SL combination that results in the lowest energy cost for a given speed (Cavanagh & Williams, 1982; Hamill, Derrick, & Holt, 1995; Knuttgen, 1961).

These observations provide evidence that runners optimize running form based on physiological criteria. Runners naturally self-select the most efficient gait characteristics commonly known as the preferred stride length (PSL) and preferred stride frequency (PSF). WhenVO_2 and SF were intentionally compared at different speeds, it was determined that VO_2 increased with reduced SF and remained the same with increased SF. In addition, PSF remained stable across three running speeds (Mercer, Dolgan, Griffin, & Bestwick, 2003).

Increased speed during endurance running is mostly achieved by increasing SL rather than SF. Long SL in humans is made possible by a combination of relatively long legs and effective leg springs (Bramble & Lieberman, 2004). Long legs increase ground contact time in running (Alexander, 1980). Relatively long contact times may be beneficial for endurance running because the inverse of contact time correlates with the energetic cost of running and it has been noted that with regard to energy cost, “running is priced by the step” (Reynolds, 1987; Bramble & Lieberman 2004).

De Wit, De Clercq & Aerts (1996) compared barefoot running with conventional shoe running and found a significantly faster SF, shorter SL and foot contact time in the barefoot condition. These results support the findings from previous studies (Komi, Gollhofer, Schmidtbleicher, & Frick, 1987; Cavanagh & Cram, 1990), and show that spatiotemporal variables are influenced by environmental changes such as the foot-ground interface (De Wit, et al., 1996). A plausible reason for the smaller step length in barefoot running could be that the runners adapt a strategy to decrease pain underneath the heel. Taking smaller steps results in a larger plantar flexion of the bare foot at touchdown.

In 2000, De Wit, De Clercq & Aerts found the change in running form between barefoot and shod running was mostly distinguished by a greater external rate of loading and a foot placement that was significantly more flat at foot strike in barefoot running. The joint arrangement of the leg is already primed in the flight phase by increased plantarflexion, by increased knee flexion and a greater velocity of knee flexion while running barefoot; this suggests that the runner dynamically adapts this strategy for barefoot running. The researchers found that plantar pressure measurements in the barefoot condition showed a significant correlation between a flatter foot placement and lower peak heel pressures (De Wit et al., 2000), and this contrasts with higher heel pressures and greater dorsiflexion in the shod condition. Results showed that runners adopt a flatter foot placement in barefoot running in order to limit heel pressure. The observed adaptations in barefoot running of shorter SL and increased SF were mainly due to changes in touchdown geometry. During the stance phase, leg stiffness is greater in barefoot running, favoring a higher SF (De Wit et al., 2000).

Lieberman (2012) found differences in SF between barefoot and shod runners. A number of studies (Divert et al., 2008; Jenkins & Cauthon, 2011; Squadrone & Gallozi, 2009) have found that SF of elite shod runners normally range between 170-180 SPM even at lower speeds such as 6 mi/hr; however, sub-elite runners frequently use a lower average SF of around150-160 SPM at similar speeds. Studies of sub-elite barefoot runners affirm that these runners have a tendency to use a higher SF than shod runners, ranging from 175-182 SPM at speeds of 6.7 mi/hr (Divert et al., 2008; Jenkins & Cauthon, 2011; Squadrone & Gallozi, 2009). By contrast, barefoot runners also have a tendency to use slower SF and longer SL when instructed to run in conventional shoes at the same speed (Divert et al., 2008; Squadrone & Gallozi, 2009).

Foot strike pattern. In addition to changes in stride length and stride frequency, the foot strike pattern changes from RFS in CS to FFS or MFS when barefoot. Because a large and rapid impact peak is painful when barefoot, especially on hard or rough surfaces, it is not surprising that habitual barefoot runners often use a MFS or FFS. While about 75% of habitually shod runners RFS at moderate speeds on flat, hard surfaces (Hasegawa et al., 2007), experienced barefoot runners are more likely to land towards the front of the foot. However, habitual barefoot runners do sometimes RFS (Lieberman et al., 2010), and it is erroneous to assume that barefoot runners always FFS.

A major aspect contributing to the majority of RFS landings in CS runners is the cushioned sole and raised heel that effectively reduces dorsiflexion by about 5 degrees, and facilitates a more comfortable RFS. Kinematic differences among foot strikes generate markedly different collision forces at the ground. Lieberman et al. (2010) compared GRF at foot strike in habitually shod and barefoot adult runners and found large GRF impact transients in RFS runners but no GRF impact transients in FFS or MFS runners, even on a steel force plate. Peak vertical force magnitudes are approximately three times lower in habitual barefoot runners who FFS than in habitually shod runners who RFS. In the majority of barefoot FFS runners, rates of loading were approximately half those of shod RFS runners (Lieberman et al. 2010).

The variation in impact peaks between different strike types can be explained by two related factors (Derrick, 2004; Nigg, 2010). The first factor is that during FFS impact, the foot is first plantarflexed and then goes through controlled dorsiflexion with an ankle that is compliant. In a RFS, however, the foot starts and remains dorsiflexed and the ankle is stiff during the same phase of time. Consequently, the effective mass or the percentage of mass that must completely stop and transfer momentum with the ground at impact is much higher with RFS (Derrick, 2004; Nigg, 2010).

The second factor, compliance, explains why FFS and some MFS create no major impact peak. Compliance is the dampening of GRF at foot strike. With RFS, a runner normally lands with more knee extension and a stiffer knee and ankle than a runner with FFS, who dorsiflexes the ankle and flexes the knee more during the phase of impact, allowing for more effective dampening of forces in the lower extremity (Lieberman et al., 2010). This example clarifies the reason why when most people jump, they land on the ball of the foot, and the principle is similarly applicable to barefoot and minimalist running, which is fundamentally repeated jumping from one leg to the other leg (Lieberman, 2012).

Compliance has some variability, and is sometimes unexpectedly high in RFS and unexpectedly low in FFS. This illustrates that a runner is able to change compliance of the lower extremity using several related strategies other than a cushioned shoe heel. Compliance can be achieved with greater knee flexion and reduced stride length (Derrick, 2004). This variability in lower extremity compliance may clarify the reason why some RFS runners wearing CS may produce lower impact forces and why some barefoot runners RFS with no heel pain or discomfort (Milner, Ferber, Pollard, Hamill, & Davis, 2006; Lieberman et al., 2010; Lieberman, 2012).

Kerrigan et al. (2009) looked at the differences in joint torques between runners in CS versus barefoot and found an average 54% increase in the hip internal rotation torque, a 36% increase in knee flexion torque, and a 38% increase in knee varus torque measured in the CS condition. The researchers postulated that the increased joint torques are likely caused by an elevated heel and built-up medial arch, characteristics of CS that encourage RFS and discourage FFS (Kerrigan et al., 2009).

As previously discussed, the longitudinal arch of the foot functionally improves the mass–spring mechanics of running by enhancing the storing and releasing of elastic energy (Ker et al., 1987). Assuming that humans evolved the elastic foot arch, this adaptation would increase performance more for non-RFS landings because the arch stretches passively during the entire first half of stance in FFS and MFS patterns (Lieberman et al., 2010). Conversely, the arch can only stretch passively later in stance during RFS running, when both the fore foot and the rear-foot are on the ground. This difference may account for the lower cost of barefoot running relative to shod running (Squadrone & Gallozi, 2009).

Metabolic Economy

The energy demand of running at a given velocity can be described in terms of caloric expenditure but it is more appropriate to refer to the aerobic demand of a given running pace. The aerobic demand is the steady state VO_2 related to a given running velocity. Terms such as energy cost and energy requirement do not accurately describe the relationship between VO_2 and running velocity. Energy cost reflects the total energy demand, which is the sum of both aerobic and anaerobic metabolism. Describing VO_2 related to a given running velocity is a useful method of comparing individuals under varying conditions, and this VO_2 gives a measure of running economy (Daniels, 1985). Therefore, the definition of running economy (RE) is the relationship between oxygen consumption (VO_2) and velocity of running (Daniels & Daniels, 1992; Saunders, Pyne, Telford & Hawley, 2004b).

Metabolically speaking, runners with poor RE use more VO_2 at the same velocity than runners with better RE. A strong relationship exists between improved RE and distance running performance. VO_2 max has historically been a standard measure of peak performance for endurance runners. However, sub-elite and elite distance runners are a homogenous group with similar VO_2 max and therefore RE may be a better predictor of performance than VO_2 max (Saunders et al., 2004b). RE is regarded as an important measure in determining success for distance runners (Daniels, 1985). Another important factor is the maximal steady state, defined as the percentage of VO_2 max a runner can sustain without exceeding the anaerobic threshold, and the ability to use fat as a fuel at high work rates in order to spare glycogen (Coyle, 1999). The running velocity coinciding with attainment of VO_2 max and the running velocity at the onset of blood lactate accumulation are also good indicators of distance running performance (Billat, Flechet, Petit, Muriaux, & Koralsztein, 1999).

In a running economy (RE) study of both elite and highly-trained distance runners, researchers sought to determine the reliability, typical error and the magnitude of smallest worthwhile change of RE (Saunders et al., 2004a). The framework from their research improves the understanding and interpretation of the significance of training interventions aimed at improving RE. In simple terms, Saunders et al. (2004a) quantified the magnitude of change in RE necessary to rule out error and a method by which to evaluate common variables that influence RE. During all RE tests oxygen consumption (VO_2), ventilation (VE), respiratory exchange ratio (RER), heart rate, stride rate, and concentration of blood lactate were determined. The results showed that RE is relatively stable, with a typical error of 2.4% for VO_2, 7.3% for ventilation, 27% for blood lactate, and ranged between 1 and 4% for RER, heart rate and stride rate. The researchers (Saunders et al., 2004b) determined that the smallest worthwhile change required in RE in highly trained distance runners is 2.4%. This means that in order for a coach or exercise physiologist to be confident of a real change, the improvement in RE must be 2.4% or greater (Saunders et al., 2004a).

Several biomechanical factors have been related to RE. According to Sauders et al. (2004b), “Running involves the conversion of muscular forces translocated through complex movement patterns that utilize all the major muscle joints in the body. High performance running is reliant on skill and precise timing in which all movements have purpose and function (Anderson, 1996)" (p. 471-472). Although biomechanical skill influences RE, much of the research focuses on physiological variables and to a lesser degree on biomechanics.

Several studies have validated the effects of shoe weight, minimalist footwear, and bare feet on RE. Previous research found that a difference of 100 grams of shoe weight relates to between ±0.5% and ±1.0% in VO_2 , and also found a 4.7% higher VO_2 in runners wearing 700-gram shoes compared to barefoot (Flaherty, 1994). In a recent study looking at effects of shoe mass and mechanics (Divert et al., 2008), weight was added to subjects' feet without adding a cushioned sole and increased energy cost was attributed to shoe mass and not gait changes. Divert et al. (2008) also theorized that the shock-absorbing properties of shoe cushioning may take away energy that might otherwise be stored and reused as elastic energy, causing a net efficiency loss.

In the present study, we reviewed the literature on barefoot running and minimalist shoes since there is very little published research about the economy of running in Vibram Five Finger shoes (VS) and because VS running simulates barefoot running with very minimally added weight.

Squadrone and Gallozi (2009) found a significant difference ($p<0.05$) in improved economy in VS shoes when compared with CS. The difference was small so they hypothesized that since the runners were trained barefoot runners, they used "barefoot-style" efficient mechanics in each footwear condition. Additionally, they found that compared to the standard shod condition, barefoot runners landed more plantarflexed and forefoot with shorter stride lengths and contact times, higher stride frequency and lower impact forces under the heel (Squadrone & Gallozi, 2009). Another recent minimal shoe study (Perl et al., 2012) found that after controlling for shoe mass, SF and foot strike type, minimal shoe running is 2.4 to 3.3% more economical than running in CS.

In contrast to the concept of cushion and support behind CS running, the popularity of barefoot and minimalist running is the hypothetical benefit of a more natural, barefoot running style. Barefoot running's characteristic foot strike patterns, stride lengths and stride rates, physiological adaptations, and running cost improvements support the hypothesis of injury prevention and improved performance (Lieberman, 2012). However, conclusions from some research on habitual RFS runners shows that some were successful and others were unsuccessful in their attempts to adapt a reduced-force barefoot strike (Dixon et al., 2005).

So while there is some evidence of improved RE with barefoot running style in minimalist and VS shoes, the evidence has not been shown to be independent of other factors such as barefoot-style running experience (Squadrone & Gallozi, 2009). For habitual RFS runners, successfully switching to VS running may require a gradual and structured training program (Vibram Fivefinger, 2012). Some research has shown that training programs designed to improve running form (e.g. Pose-method) negatively affects RE (Dallam, Wilber, Jadelis, Fletcher, & Romanov, 2005). More research is needed to determine the trainability of minimalist running and effects on RE. While evidence strongly supports the inverse relationship between RE and shoe weight, the biomechanical effects of minimalist shoes on RE is less clear.

Summary of Literature Review

This review covered evidence supporting the evolutionary basis of barefoot endurance running in humans and the connection that evolution has to efficient running. There are clear differences between running in conventional shoes and running in minimalist shoes. The prescription of conventional cushioned, thick heeled, arch supported shoes is not evidence-based. Although research has shown that reduced weight of minimalist shoes improves economy, there is less evidence about biomechanical efficiency improvements.

Biomechanical efficiency estimates the amount of mechanical work accomplished per the amount of energy expended. Efficiency calculation methods need more perfecting since running is such a complex movement pattern, but efficiency is a useful parameter for hypothesis testing in energetics and mechanics. A validated, reliable method is needed for calculating biomechanical efficiency.

Among the many adaptations that have enabled humans to become endurance-running specialists, the Achilles tendon and foot arch may improve efficiency up to 50%. The mass-spring mechanism depends on efficient “barefoot-style” stride mechanics such as shortened stride length and increased stride frequency. However, the imposition of thickly heeled, arch-supported footwear may be a problematic factor in efficient running. Research shows that a majority of runners have a RFS pattern in CS that precludes efficient barefoot-style mechanics.

Conversely, FFS and MFS is common in barefoot running; the mass-spring mechanism is in effect, which reduces GRF three-fold compared to RFS running and reduces energy consumption. Recent research shows similar foot strike pattern, reduced

GRF and reduced energy consumption with minimalist shoes. More running efficiency research is needed comparing conventional and minimalist footwear.

Since minimalist shoe running is growing in popularity, it raises many questions about optimal running footwear design. The popularity of minimalist running is due to the perceived benefits of more natural, barefoot-style mechanics. This review of literature sought to highlight different factors that are attributable to performance, efficiency and economy relating to minimalist and Vibram Five Fingers footwear.

This study seeks to identify whether or not biomechanical efficiency and metabolic economy differences occur naturally when footwear changes from conventional to minimal. The development of this study is discussed in detail in Chapter Three: Methods.

Chapter Three: Methods

Research Design

Researchers in this study used repeated measures ANOVA to analyze differences in economy. Researchers used paired t-tests to analyze differences in respiratory exchange ratio (RER), heart rate (HR), rating of perceived exertion (RPE), stride length (SL), stride frequency (SF), vertical hip displacement, and variables that occurred at the instance of foot strike: foot strike pattern, horizontal ankle to hip distance, hip flexion angle, knee flexion angle, and ankle plantarflexion angle. Researchers completed statistical analyses using Microsoft Excel 2010 Analysis Tool pack. The criterion alpha was accepted at the .05 level of significance.

Sample

The subject sample was comprised of competitive, trained distance runners and triathletes within the age range of 18-35 years who were capable of running a 5-kilometer race within 20 minutes or faster. This inclusion criterion was necessary in order to select subjects capable of successfully completing simulated race performance test conditions. The sample included both male and female runners. Other inclusion criteria included the successful completion of a respiratory functional capacity test (FVC) within the normal range of 3-5 liters (Hankinson, Odencrantz, & Fedan, 1999). Exclusion criteria included age outside of the 18-35 year range, 5-kilometer race finish slower than 20 minutes or failure to meet the protocol-required steady state VO_2.

All subjects were residents of Sonoma County, California, and their average characteristics were as follows: age 25.4 years, weight 161.5 pounds, height 5’ 10.2” and VO_2-max of 60.2 ml • kg^{-1} min^{-1} (See Table D.1 in Appendix D). Researchers did not control for minimalist shoe running experience. Based upon subjects' reports, the sample was comprised of four minimalist-experienced and six minimalist-inexperienced runners. Minimalist-experienced subjects ran barefoot or minimalist at least one hour per week for at least 3 months. Due to constraints of time, subject availability, subject inclusion criteria, and resources, the sample size was limited to ten subjects: nine male and one female. The researchers made an effort to recruit as many subjects as possible to ensure that the sampling was more representative of the population. Approximately 50% of subjects seeking to participate in the study were accepted.

Participants were given full disclosure about the nature of the study, their right to refuse participation, risks and benefits of the research, and the researcher's responsibilities, when informed consent was obtained (Appendix A). The proposal for this study involving human subjects was submitted to the Sonoma State University (SSU) Institutional Review Board for approval before obtaining any data (Appendix E).

Setting

The sample was obtained by sending a recruitment announcement via e-mail to the SSU Women's Cross Country Team, the SSU Triathlon Club, and The Empire Runners Club of Sonoma County, requesting their participation (Appendix B). This population represented high-level, non-elite runners and triathletes that met the study inclusion criteria. The exercise testing and research was conducted in the SSU Human Performance Lab over an eight-week period. Twelve subjects underwent the full protocol of exercise testing but only 10 subjects met the inclusion criteria.

Testing Procedure

VO_2 max testing. Each subject came to the SSU Human Performance Lab on the first visit for a modified Bruce VO_2-max test. Upon arriving in the lab, each subject's body weight and height was recorded. Subjects performed a vital lung capacity test using a digital spirometer. Each subject wore conventional shoes, headgear for ventilatory measurements and a Polar heart rate monitor. After the protocol was explained, the subject was connected to the Parvomedics metabolic measurement cart (e.g. mixing chamber, gas analyzer and computer) and performed the VO_2-max test on the Quinton treadmill. The protocol consisted of increases in grade and speed every three minutes in the following order: 1% at 4 mi/hr, 2% at 6 mi/hr, 3% at 8 mi/hr, 4% at 10 mi/hr and 5% at 12 mi/hr. Heart rate and rating of perceived exertion (RPE) was collected at regular intervals during the entire duration of the test. The subject continued until they voluntarily stopped or could no longer conform to the protocol.

Submaximal testing. Upon arriving in the lab on the second visit for the two submaximal tests, subject's body weight and both CS and VS weights were recorded. The coin-toss method was used to randomize the testing order and determine which footwear was to be worn first. The subject wore headgear and a Polar heart rate monitor. For collecting lower extremity kinematic data, body markers were attached at the iliac crest, the greater trochanter, lateral condyle of the femur, lateral malleolus, tuber calcaneum, and fifth metatarsophalangeal joint of the foot.

The protocol was explained, the subject was connected to the metabolic cart and performed the testing on the treadmill which was set at 1% grade (Jones & Doust, 1996). The continuous protocol consisted of speed changes as follows: 3 minutes at 3.5 mi/hr, 5 minutes at 6.0 mi/hr, 3 minutes at 3.5 mi/hr, 5 minutes at 7.5 mi/hr, 3 minutes at 3.5 mi/hr, 5 minutes at 9.0 mi/hr and 3 minutes at 3.5 mi/hr. Heart rate and RPE was collected at regular intervals during the entire duration of the test. Saggital plane 210 hertz video was recorded with a Casio EXFH 1000 camera mounted on a tripod at a distance 10 feet away from the treadmill during the last 2 minutes of the 9.0 mi/hr stage. After completion of the first submaximal test, the subjects took 10-minute rest breaks, then changed to the alternate footwear condition and the same protocol was repeated.

Data Collection

Video data. High-speed video in the saggital plane was captured in order to examine spatiotemporal and kinematic variables. Video was captured from the last 2 minutes of the 9 mi/hr stage for each submaximal test condition. A meter stick was used as a reference for digitizing.

Metabolic data. In order to ensure reliability, the metabolic cart was calibrated before each testing session. RER, VE and VO_2 were captured from subjects' expired ventilation through the mixing chamber and metabolic cart with constant recording by computer software. Lab assistants recorded heart rate each minute from a Polar heart rate monitor. RPE was recorded at the beginning of the last minute of each stage. Subjects indicated their RPE by pointing to a validated (Robertson et al., 2004) Borg scale of perceived exertion (Appendix C).

Data Analysis

Video data. Video files were converted from raw format to AVI and trimmed using Quicktime Pro 7.7.1 software in order to capture the first full stride sequence, from right toe off (RTO) through complete right foot strike (RFS). Each anatomical marker point was manually digitized with KA PRO 7 kinematic analysis software through one complete stride sequence in order to enable the calculation of stride length, stride frequency, hip vertical displacement, and variables occurring at foot strike: horizontal distance from ankle malleolus to hip joint, hip flexion angle, knee flexion angle, and ankle plantarflexion.

Stride length was calculated from the digitized full stride sequence RTO to RFS as the following mathematical product: (9 mi/hr) (1 hr/3600 sec) (1609 meters/mile) (1 sec/420 frames) (frames RTO to RFS/1 stride) = stride length (meters). Stride frequency was calculated from the digitized sequence RFS to RFS as the following mathematical product: (1 stride/frames RFS to RFS) (420 frames/sec) (60 sec/min) = strides per minute. The ankle malleolus to hip horizontal distance was measured in freeze frame on KA PRO 7 as the difference between the malleolus x-position and the hip x-position at the instance foot strike. Vertical hip displacement was calculated using KA PRO 7 as the mathematical difference between the maximum and minimum y-position of the hip over the time course of one complete stride. Angular measurements at the hip, knee and ankle at the instance of foot strike were calculated from KA PRO 7.

Metabolic Data. VO_2 data was averaged over the final two minutes of each 5-minute submaximal stage. Exclusion criteria for steady state VO_2 data was defined as RER>1.0, a change in VO_2>100 ml/min during the last two minutes of the stage, or a clear indication of ventilatory threshold (Sawyer et al., 2010; Foster & Lucia, 2007). Although researchers commonly accept 5 kcal as the caloric equivalent of 1 liter of inspired oxygen during steady state exercise (McCardle et al., 2010), this approximation does not consider the variability in simultaneous contributions of carbohydrate and fat.

Garby and Astrup (1987) challenged the validity of the 5 kcal/liter VO_2 equivalency arguing that the respiratory quotient varies with exercise intensity and reflects the variability in substrate utilization. Therefore, the validity of the caloric estimate of oxygen consumption is improved by using the equation based on the stoichiometric relationship between VO_2 and RER, given by $(4.94 \bullet RER+16.04)/60 \bullet VO_2$.

Calculation of biomechanical efficiency. Efficiency is an indicator of the biomechanical skill in running that orchestrates the spatiotemporal and kinematic factors to move the body forward with the least energy cost. The delta efficiency is the ratio of the change in external mechanical work to the change in metabolic energy input across treadmill speeds. Delta efficiency was calculated, using the method described by Bijker et al. (2001a), from mechanical work in watts defined as $Pmech = (m)(v)(\sin \theta)$, the metabolic energy input in watts defined as $Pmet = (4.94 \bullet RER+16.04)/60 \bullet VO_2$ and the percentage delta efficiency defined as $\Delta E= (\Delta Pmech/\Delta Pmet) \times 100$.

Collection of foot strike pattern data. Using KA PRO 7 kinematic analysis software, foot strike pattern was determined by freezing the video of the subject's foot at the moment of foot strike. Researchers categorized the type of foot strike based upon norms established in other research (Altman & Davis, 2010). The observation method used by the researchers divided the length of the foot into equal thirds. The representations of foot strike were as follows: striking the rearmost third of the foot was RFS, striking the middle third of the foot was MFS and striking the front third of the foot was FFS.

Results were presented in data and tables, graphs and schematics. The following chapter outlines the results of this study.

Chapter Four: Results

Metabolic, physiological and video data collected during submaximal treadmill tests in Vibram Five Fingers and conventional shoe conditions yielded results in biomechanical efficiency and metabolic economy. Additional physiological results include heart rate (HR), respiratory exchange ratio (RER) and rating of perceived exertion (RPE). Biomechanical results also include stride length (SL), stride frequency (SF), vertical hip displacement, and variables captured at foot strike: horizontal ankle to hip distance, hip flexion angle, knee flexion angle and ankle plantarflexion angle (See Table D.2 in Appendix D for raw data).

Biomechanical Efficiency

Delta efficiency values were stable between VS and CS conditions and across treadmill speeds (Table D.3 in Appendix D). Group mean delta efficiencies were similar and slightly higher in the VS condition (14.5 %) than in the CS condition (14.2%) and the difference was not significant ($p<0.89$).

Metabolic Economy and Physiological Variables

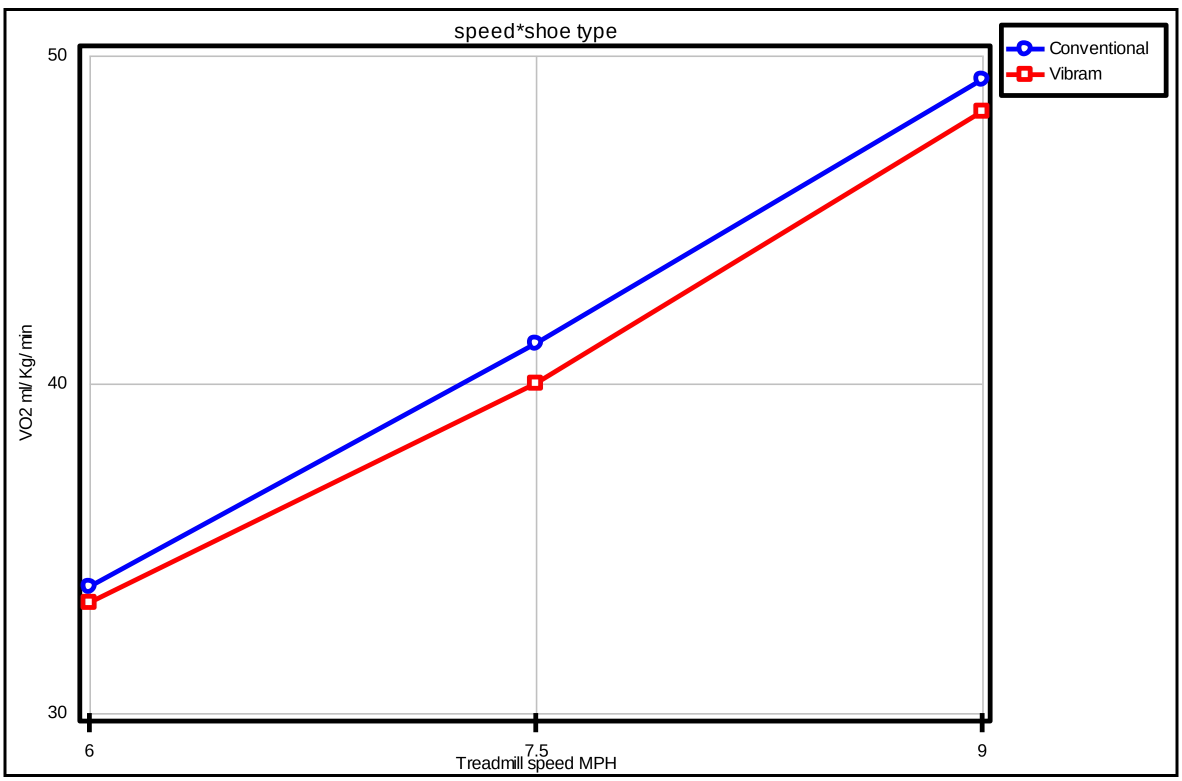
Dependent physiological variables were similar across footwear conditions and treadmill speeds. Oxygen consumption was slightly lower in the VS condition than in CS condition (See Figure 1 below and Table D.4 in Appendix D); this was a clear trend but the result was not significant ($p<0.93$). Average respiratory exchange ration (RER) was similar between conditions but slightly lower in the VS condition and the difference was not significant ($p<0.69$). Average heart rate at 9 mi/hr was slightly lower in VS and the one-tailed probability was significant ($p<0.04$). Rating of perceived exertion (RPE) values in the VS condition were slightly lower and the difference not statistically significant (p<0.51). (See Table 1).

Biomechanical Variables at 9 mi/hr

Spatiotemporal variables. Average stride length at 9 mi/hr was slightly greater in VS than in CS but very similar and not statistically different (p<0.47). Average stride frequency at 9 mi/hr was slightly higher in VS than in CS but and not statistically different (p<0.48). Vertical hip displacement was slightly greater in VS but not significant (p<0.54). (See Table 1)

Figure 1

Metabolic Economy: Conventional Shoes vs. Vibram Five Finger Shoes



Kinematic variables. Average ankle to hip horizontal distance at the instance of foot strike was slightly lower in the VS but the difference was not significant (p<0.43).

Average hip flexion angle at foot strike was slightly less in VS but not significantly different from CS ($p<0.37$). Average knee flexion angle at foot strike was slightly greater in VS but was not was significant ($p<0.09$). Lastly, the average ankle plantarflexion in VS was greater at foot strike than in CS and the difference was significant ($p<0.01$). (See Table 1).

Table 1

Efficiency, Physiological, Spatiotemporal and Kinematic Variables

Variables	Conventional shoes	Vibram Five Finger shoes
Efficiency (%)	14.2±.01	14.5±.01
VO_2 (ml/kg/min)	41.4±3.3	40.6±2.9
RER (VCO_2/VO_2)	0.93±.05	0.92±.05
Heart rate (bpm)	169±10.8	167±10.3*
RPE (6-20)	12.8±2.7	12.6±2.5
Stride length (m)	0.89±.09	0.90±.08
Stride frequency (steps per minute)	173±9.8	175±10.3
Vertical hip displacement (cm)	15.8±5.5	16.1±4.5
Ankle to hip distance at foot strike (cm)	28.6±8.4	27.3±9.6
Hip angle at foot strike (deg)	28.5±16.0	25.5±14.6
Knee angle at foot strike (deg)	17.6±6.8	23.0±10.2
Ankle plantarflexion at foot strike (deg)	84.5±11.4	93.3±11.0**

Note: Mean ± SD of 10 subjects; *single-tailed ($p<0.05$), **($p<0.01$)

Foot-strike pattern. Observed foot strike patterns varied in both minimalist-experienced (ME) and minimalist–inexperienced (MI) groups. Two ME subjects and one MI subject transitioned from RFS to non-RFS. Two ME subjects and five MI subjects did not transition from RFS to non-RFS (See Table 2).

Table 2

Foot-Strike Pattern Transition Schema, CS to VS, by Minimalist Running Experience Level

Minimalist-experienced		Minimalist-inexperienced	
Frequency	Transition	Frequency	Transition
1	R→R	3	R→R
2	R→M	1	R→F
1	M→M	2	F→F

Note: N=10; R=RFS; M=MFS; F=FFS

In the next chapter, the results are synthesized with the literature to present the conclusions of this study: what can we learn about the efficiency and economy of running from the way runners adapt their biomechanics to running in minimalist shoes?

Chapter Five: Discussion

The purpose of the present study was to test the claim by the Vibram Company that runners wearing Vibram Five Finger shoes (VS) make immediate improvements to their running form that cause them to run more efficiently than runners wearing conventional shoes (CS). The hypotheses that we tested in this study are as follows:

1. VS running is biomechanically more efficient than CS running due to alterations in running kinematics and kinetics.
2. VS running is more economical than CS running due to reduced shoe mass and altered running biomechanics.

Biomechanical Efficiency

Efficiency results in the study failed to support the hypothesis that VS running is biomechanically more efficient than CS running due to alterations in kinematics and kinetics. In all exercise intensities, average efficiencies were consistently higher in the in the VS condition than in the CS condition, the difference was not significant ($p<0.89$). The similarity in average efficiency between footwear conditions is not consistent with other research since differences in shoe weight alone have significantly influenced oxygen consumption and efficiency (Flaherty, 1994; Divert et al., 2008). The relative stability in efficiency across footwear conditions may be due to the low percentage (30%) of subjects who changed foot-strike pattern from RFS to MFS or FFS. Research has shown that the change from RFS to non-RFS in barefoot or minimalist footwear running facilitates the “mass-spring mechanism” of the Achilles tendon and foot arch, which reduces energy consumption and increases efficiency (Bramble & Lieberman, 2004; Lieberman et al., 2010). Therefore, the apparent stability of the biomechanical efficiency of runners in this study may be attributable to the relative stability of foot-strike patterns across footwear conditions (See Foot Strike Pattern section).

Metabolic Economy and Physiological Variables

Metabolic economy. Economy results failed to support the hypothesis that running in VS is more economical than running in CS due to shoe mass and altered biomechanics. Average VO_2 was slightly lower in the VS condition across treadmill speeds and this was a clear trend but the result was not significant ($p<0.93$). The magnitude of change (1.9%) in VO_2 from the present study was slightly below the criteria for the smallest worthwhile change in economy, considered 2.4% by Saunders et al. (2004). The smallest worthwhile change is the minimum change, ruling out error, necessary to be confident that a real change in economy has occurred.

Economy results from the present study are inconsistent with previous research that found a difference of 100 grams of shoe weight relates to between ±0.5% and ±1.0% change in VO_2, and also found a 4.7% higher VO_2 in runners wearing 700-gram shoes compared to barefoot (Flaherty, 1994). Additionally, a recent study by Perl et al. (2012) found that after controlling for shoe mass, SF and foot strike type, minimal shoe running is 2.4 to 3.3% more economical than running in CS.

The small magnitude of change in economy between footwear conditions in the present study may be attributed to the relative stability of foot-strike pattern across conditions. Since the magnitude of change in economy fails to meet the criteria of the smallest worthwhile change, errors such as uncontrolled variables cannot be ruled out. In similar studies (Perl et al., 2012), intervening variables were more rigorously controlled. Within this group of highly trained runners, similar economy results across conditions may be attributable to the ability of the subjects to maintain efficient stride mechanics across footwear conditions (De Wit et al., 1996). The high skill level of subjects in adapting stride mechanics to varying foot-ground interfaces may have reduced the variability in economy between conditions.

Other physiological variables at 9 mi/hr. Average respiratory exchange ratio (RER) at 9 mi/hr was similar between conditions but slightly lower in the VS condition and the difference was not significant ($p<0.69$). The magnitude of difference in average RER between conditions was small (1.1%) but trended similarly as average VO_2. (See Metabolic Economy section). The average RER values (0.93, 0.92) for CS and VS, respectively, were relevant in this study because they validated submaximal exercise intensity level (Amman et al., 2004). Results from a recent study showed no significant change in heart rate (HR) between VS and CS running (Squadrone & Gallozi, 2009). In the present study, average HR at 9 mi/hr was slightly lower in VS and the single-tailed probability is significant ($p<0.04$). Difference in HR between conditions was small and trends similar to values of average VO_2 since HR fluctuates proportionally with VO_2 during dynamic exercise (Roitman & Kelsey, 1998).

Rating of Perceived Exertion (RPE) values in the VS condition were slightly lower and the difference not statistically significant ($p<0.51$). The RPE scale is a validated perceptual metric for assessing intra- and inter-subject exertional responses during dynamic exercise. RPE results from this study are consistent with other research that shows a linear relationship to HR and VO_2 responses (Robertson et al., 2004). RPE was relevant to this study since the less-supportive minimalist footwear had the potential to cause discomfort and change exertion level and perception of exertion.

Biomechanical Variables at 9 mi/hr

Spatiotemporal variables. Average stride length (SL) at 9 mi/hr was slightly longer in VS than in CS but similar and not statistically different ($p<0.47$). This slightly greater average SL in the VS condition is inconsistent with other research that shows shorter SL in the barefoot condition (De Wit et al., 1996), and in the VS condition (Squadrone & Gallozi, 2009). Average stride frequency (SF) at 9 mi/hr was slightly higher in VS than in CS but not statistically different ($p<0.48$). The similarity in average SF between conditions is not consistent with other research that has shown significant increases in SF in VS when compared to CS (Squadrone & Gallozi, 2009). However, the change to a shorter SL and increased SF in barefoot-style running was found to be due to changes in "touchdown geometry" or foot-strike pattern (De Wit et al., 2000). Therefore, the slight unexpected increase in average SL and the slight increase in SF in the VS condition may be due to the relatively small number of subjects whose observed foot strike pattern changed to a barefoot-style from a RFS.

Vertical hip displacement. Average vertical hip displacement (VHD) was slightly greater in the VS condition but not significantly different ($p<0.54$). The slightly larger VHD found in the VS condition is consistent with other research on barefoot running and vertical leg compliance. Vertical leg compliance is defined as the drop in the body's centre of mass relative to the vertical force during the period of impact. Vertical compliance is greater in FFS running than in RFS running, leading to a lower rate of loading. More compliance during the impact period in FFS runners is explained by a greater drop in the centre of mass resulting partly from ankle dorsiflexion and knee flexion (Lieberman, et al., 2010). The slightly increased average VHD in the VS condition in the current study supports the idea that runners adopt more compliant mechanics in VS. The slightly increased average VHD may be due to the relatively low percentage of subjects whose foot strike pattern changed from RFS to FFS or MFS.

Kinematic variables. Average ankle to hip horizontal distance at the instance of foot strike was slightly less in the VS but the difference was not significant ($p<0.43$). Lesser horizontal distance from the foot to the body center of mass at foot strike mean a more compliant landing that is consistent with barefoot-style running mechanics (Lieberman, 2012).

Average hip flexion angle at foot strike was slightly less in VS but not significantly different from CS ($p<0.37$). Average knee flexion angle at foot strike was slightly greater in VS but was not was significant ($p<0.09$). Similar to other research (Squadrone & Gallozi, 2009), the average ankle plantarflexion was greater at foot strike in VS than in CS and the difference was significant ($p<0.01$). Average kinematic results were similar across footwear conditions and not significant excepting ankle plantarflexion. However, results of joint angle measurements at the hip, knee and ankle are interrelated as a kinematic chain and trend slightly toward characteristic barefoot-style touchdown geometry. Research has shown that the joint arrangement of the leg is already prepared in the flight phase by increased plantarflexion, by increased knee flexion and a greater velocity of knee flexion while running barefoot; this suggests that the runner dynamically adapts this strategy for barefoot running (De Wit et al., 2000). The average ankle plantarflexion was significantly greater in the VS condition; this result is plausible due to the observed 30% of runners who changed their foot strike pattern from RFS to non-RFS. The small, non-significant difference in overall kinematic variables is consistent with the low frequency of observed foot strike transition from RFS to MFS or FFS.

Foot-strike pattern. Observed foot strike patterns at the instance of foot strike varied between footwear conditions and with the experience level in minimalist running. Four subjects maintained RFS across footwear conditions, two subjects changed from RFS to MFS and one changed from RFS to FFS. Two subjects maintained FFS and one maintained MFS across conditions.

To reiterate, research has shown that the joint arrangement of the leg is already prepared in the flight phase by increased plantarflexion, by increased knee flexion and a greater velocity of knee flexion while running barefoot and that the runner dynamically adapts touchdown geometry for a more compliant landing (Dewitt et al., 2000).

In this study, foot strike pattern varied widely between subjects (5 variations) but varied less within subjects (3 variations). Seven out of ten subjects in the study RFS in CS but only two of them changed to MFS and one changed to FFS; this means that only 30% of the subjects in the study changed from RFS to non-RFS, which may explain the stability in the efficiency and economy results across footwear conditions.

The overall foot strike results in the present study do not support the hypothesis that subjects in VS will make immediate improvements to their running form that cause them to run more efficiently than in CS. Notably, however, foot strike transitions from RFS to non-RFS were twice as frequent in minimalist-experienced runners. Even more notably, 67% of minimalist-experienced subjects in the present study who RFS in the CS condition transitioned to non-RFS but only 25% of minimalist-inexperienced runners transitioned. These results are consistent with other research about conventional shoes and RFS (Hasegawa et al., 2007).

Unlike another study comparing Vibram Five Fingers and conventional shoes with trained barefoot runners (Squadrone & Gallozi, 2009), minimalist running experience level of subjects in the present study was mixed, with a slight majority being inexperienced (60%). Minimalist-inexperienced subjects more frequently RFS and minimalist-experienced subjects more frequently transitioned from RFS to non-RFS but only three subjects in total transitioned. The overall stability in foot strike pattern across footwear conditions resulted in relatively stable results in efficiency, economy and related physiological and biomechanical variables.

Study Limitations

The study was mainly limited by the lack of availability of resources, equipment and subjects. With limited access to local runners experienced in minimalist running, a major limitation of the study was the mixed level of minimalist running experience in the sample. Potential sources of error include the quality of the video files and the manual digitizing of the video files for the kinematic analysis. The calculation of biomechanical efficiency was limited since the calculation included the estimate of external work but not the internal work of the body and body segments. Lastly, the notable confounding variables in this study include the subjects' level of minimalist running experience, foot strike pattern, stride frequency and shoe weight.

Implications

This study will contribute to the body of knowledge regarding running efficiency, economy and running technique as they relate to minimalist footwear. Since the sport of running is currently in the midst of the largest popularity surge ever recorded, accurate scientific information regarding newly popular minimalist running shoes is critically important to all runners, coaches, medical professionals and fitness professionals. Runners armed with knowledge about the potential implications, benefits and risks involved with minimalist running will be empowered to apply such knowledge to improve performance, reduce injury and enjoy running well into old age.

Recommendations for Future Research

Future research comparing efficiency and economy differences between running in Vibram Five Finger shoes and conventional shoes should control for confounding variables such as minimalist-running experience level, foot strike pattern, stride frequency and shoe mass. Validated and reliable methods for calculating biomechanical efficiency are needed. Future studies with larger sample sizes are needed for greater statistical power. Longitudinal studies are needed that analyze the long-term effects of minimalist shoe training on biomechanical efficiency, metabolic economy, and kinematics. Studies are also needed to identify contraindications to minimalist shoe running and effective training programs appropriate to individual runners based on their personal attributes.

Conclusion

This study sought to test the hypothesis that Vibram Five Fingers shoes cause runners to make immediate improvements to their running form, which effectively improve biomechanical efficiency and metabolic economy. Although results showed slight trends toward improved efficiency, economy and related kinematic changes, the differences were not statistically significant excepting ankle dorsiflexion and heart rate (both measured at 9 mi/hr).

Efficiency results failed to support the hypothesis that VS running is biomechanically more efficient than CS running due to alterations in kinematics and kinetics. The relative stability in efficiency across footwear conditions may be due to the low percentage (30%) of subjects who changed foot-strike pattern from RFS to MFS or FFS. Similarly, economy results also failed to support the hypothesis that running in VS is more economical than running in CS due to shoe mass and altered biomechanics. Average VO_2 was slightly lower in the VS condition across treadmill speeds and this was a clear trend but the result was not significant ($p<0.93$). The magnitude of change (1.9%) in VO_2 from the present study did not meet the criteria for the smallest worthwhile change (2.4%). Other physiological variables measured at 9 mi/hr: RER, HR and RPE were consistent with economy results since they were similar and not statistically different, excepting HR. It is plausible that the stability of foot strike patterns across footwear conditions explains the relative stability in economy and other physiological variables across conditions.

Spatiotemporal and kinematic results measured at 9 mi/hr were consistent with efficiency, economy and physiological results since they did show slight, non-significant trends (excepting ankle plantarflexion) towards improved, barefoot-style mechanics. Average ankle plantarflexion was significantly greater in the VS condition ($p<0.01$); this result may be due to a large magnitude of change in plantarflexion in subjects who changed from RFS to non-RFS pattern.

Results showed an unexpected slight, non-significant *increase* in SL in the VS condition that was likely due to methodological or equipment error. The small, non-significant difference in overall spatiotemporal and kinematic variables in the VS condition trended towards improved barefoot-style running mechanics. This may be due to the variability in minimalist experience since experienced subjects transitioned more frequently from RFS to non-RFS and inexperienced subjects transitioned less frequently from RFS to non-RFS.

Since minimalist running experience was an uncontrolled variable, RFS was stable across shoe conditions in three inexperienced subjects. Four other subjects also had stable foot strike patterns across footwear conditions. Only three subjects transitioned from RFS to non-RFS and the other seven subjects' foot strike pattern remained stable. The stability of foot strike pattern across footwear conditions may explain the relative stable results in efficiency, economy, and biomechanical variables. The small, mostly non-significant trends in the results towards improved efficiency and economy may be explained by the relatively small proportion of the sample (30%) who transitioned from RFS to non-RFS, which is characteristic of "barefoot-style" mechanics.

The evidence from this study clearly does not support the claim by the Vibram Company that wearing Five Finger Shoes immediately improves running form and efficiency. Biomechanical efficiency and metabolic economy are influenced by multiple factors. Improving running form and biomechanical efficiency is not merely as simple as just changing from conventional shoes to minimalist footwear. Although sensory feedback from the feet in VS may improve and help induce MFS or FFS, results from this study show stability in foot strike pattern across footwear conditions. It is dubious to assume a cause and effect relationship between simply wearing minimalist shoes and improved running mechanics. Results showed that 67% of minimalist-experienced runners transitioned from RFS to non-RFS, but only 25% of minimalist-inexperienced subjects transitioned from RFS to non-RFS. Based on the results, we hypothesize that training in minimalist shoes such as Vibram Five Fingers may help to habituate runners to barefoot-style foot strike patterns and improve efficiency and economy, but training may be more influential than footwear.

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APPENDICES

APPENDIX A

Informed Consent

SONOMA STATE UNIVERSITY

INSTITUTIONAL REVIEW BOARD FOR THE RIGHTS OF HUMAN SUBJECTS

INFORMED CONSENT GUIDANCE

Checklist for Informed Consent

Use the following list to confirm that all required elements of informed consent are included in your attached consent form. Informed consent is required from all subjects regardless if the study qualifies for exemption or expedited review.

1. The participants are informed that they are involved in research. Students must specify that the research is being done as part of a class or for a master's degree at Sonoma State University.
2. There is a clear statement of the purpose of the research.
3. There is a description of the procedures to be followed in the research project.
4. The participants are informed of the duration of their participation and the time commitment expected of them.
5. There is a description of any foreseeable risks and discomforts.
6. There is a description of any benefits possible to the participant or others expected from the research. ("Benefits" refers to direct benefits; statements that the research may add to the total body of knowledge in the relevant field of study are inappropriate. If the participant will receive no benefits, this should be explicitly stated.)
7. There is an explanation of the procedures by which the participant's confidentiality will be protected.
8. There is a statement that participation is voluntary, that there is no penalty for refusal to participate, and that the subject may withdraw at any time without penalty.
9. If the participant does not speak English or is significantly disabled either emotionally or intellectually, the consent form is in a language which the subject can be expected to comprehend. (Include if applicable.)
10. If the researcher has a legal obligation to report an act to authorities, participants are so informed. (Include if applicable.)
11. Researcher's name and the telephone number where researcher can be contacted for answers to questions are provided.
12. For student researchers, the name, telephone number, and email address of the professor or faculty advisor is provided.
13. If the research involves minors (under age 18) there is (a) an informed consent form for the parent/guardian and (b) an informative letter or script that explains the project to the minor, written in language appropriate for the participant's age.

Waiver of Written Informed Consent

Waiver of written informed consent will be considered for situations such as the following:

1. The subjects are from cultures that use oral rather than written traditions.

2. Written consent might greatly hinder rapport in building cross-cultural and/or cross-ethnic research.
3. The subject has sought participation in an adequately publicized activity.
4. The subject comes from a class of people well able to protect themselves, such as public officials and university administrators, and is being questioned on matters pertinent to his/her profession.
5. The research is performed using existing data held by a third party and no identification is possible.
6. Written informed consent would make research impossible, such as with telephone surveys.

The IRB reviews each request individually, considering all aspects of the particular study. Requests for waiver must be in writing, providing a thorough explanation of the situation and a description of the proposed alternative method of obtaining informed consent. If oral consent is planned, a text of the oral statement must be submitted.

Informed Consent to Participate in Exercise Testing

You are invited to participate in a study comparing the efficiency of running in Vibram Five Fingers (VFF) shoes as compared to running in conventional running shoes (CRS). The study is being conducted by Joseph Bootier and Jordan Smith, graduate students in Kinesiology; and Dr. Bulent Sokmen, PhD., Exercise Physiology Professor, and Dr. Wanda Boda, PhD., Biomechanics Professor at Sonoma State University. We hope to learn if there are any differences in metabolic or biomechanical efficiency between VFF and CRS treadmill running. You were selected as a participant for this study because you are a trained runner.

If you decide to participate, you will get a free VO_2 max exercise tests on the treadmill and $20. You will run a VO_2 max test in CRS on the first testing day and then run a sub-max test in VFFs on the second testing day. We will be collecting respiratory exchange ratio, VO_2, and capturing video during treadmill test. A VO_2 max exercise test is inherently strenuous and discomfort associated with maximal exercise effort is expected. Vibram Five Fingers shoes are an alternative shoe technology and may cause foot discomfort. We cannot and do not guarantee or promise that you will receive any benefits from this study except the free VO_2max test and $20.

Any information that is obtained in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission or as required by law. If you give us your permission by signing this document, we plan to submit this study for journal publication.

There are potential risks associated with running a graded exercise test such as musculoskeletal injury, abnormal blood pressure, fainting, irregular heart beat, and in rare instances heart attack, stroke, or death. Emergency equipment and trained personnel are available to deal with unusual situations that may arise. If you are physically injured as a result of participating in this project, you may call 664-2166 at Sonoma State University for information on filing a claim.

Your decision whether or not to participate will not prejudice your future relations with Sonoma State University. If you decide to participate, you are free to withdraw your consent and to discontinue participation at any time without prejudice.

If you have any questions, please ask us. My name is Joe Bootier and I can be reached at 415-748-7272 jbootier@gmail.com My advisor Dr. Lauren Morimoto, PhD., can be reached at (707)664-2479 morimoto@sonoma.edu

You will be given a copy of this form to keep. YOU ARE MAKING A DECISION WHETHER OR NOT TO PARTICIPATE. YOUR SIGNATURE INDICATES THAT YOU HAVE DECIDED TO PARTICIPATE HAVING READ THE INFORMATION PROVIDED ABOVE.

Date	Signature of Participant	Printed Name of Participant
Date	Signature of Principal Investigator	Printed Name of Principal Investigator
Date	Signature of Witness	Printed Name of Witness

APPENDIX B

Recruitment Announcement

Recruiting Participants for a Research Study

Efficiency of Treadmill Running: Vibram Five Fingers Versus Conventional Running Shoes

WHAT…

The purpose of this research is to test claims made by the Vibram company that running in Vibram Five Finger shoes is more efficient than running in conventional running shoes. During treadmill running tests, biomechanical and metabolic data will be collected through video capture and VO_2 measurement. Participants will complete two testing sessions. A VO_2max test will be completed during test session #1. Two submaximal tests will be completed during test session #2, one submaximal test per each footwear condition.

WHO…

The researchers are seeking to recruit experienced, competitive distance runners between the ages of 18-35. You must be uninjured and able to run at least one hour straight, run 25 miles or more per week and average a 6:30 minute per mile 5K/10K race pace or faster. Participants will receive a free VO_2max test and $20.

THE RESEARCHERS...

The research is being conducted by Masters students Joe Bootier and Jordan Smith under the supervision of Dr. Bulent Sokmen, PhD., Dr. Wanda Boda, PhD., and Dr. Lauren Morimoto, PhD. in the department of Kinesiology at Sonoma State University.

This study will conform to and comply with the Institutional Review Board for the rights of human subjects at Sonoma State University, Rohnert Park, CA.

If you are interested in participating, please respond by email to bootier@seawolf.sonoma.edu Please include your phone number and your average 5K/10K race pace. Thank you.

APPENDIX C

Borg Scale

The Borg Category Rating Scale

Least effort		
6		
7	very, very light	
8		
9	very light	
10		
11	fairly light	ENDURANCE TRAINING ZONE
12		
13	somewhat hard	
14		
15	hard	STRENGTH TRAINING ZONE
16		
17	very hard	
18		
19	very, very hard	
20		
Maximum effort		

APPENDIX D

Supplemental Tables

Table D.1

Subject Characteristics

Subject Characteristics				
	Age (yrs)	Weight (lbs)	Height (feet/in)	VO2 max (ml/kg/min)
	19.0	154.0	6.0	52.0
	31.0	174.0	6.0	75.0
	22.0	157.0	5' 11	64.0
	28.0	155.0	6.0	64.0
	21.0	147.0	5' 9	51.0
	23.0	151.0	5' 9	60.0
	35.0	159.0	5' 7	56.0
	22.0	145.0	5' 9	57.0
	35.0	192.0	5' 8	57.0
	18.0	181.0	6' 1	66.0
Average	25.4	161.5	5' 10	60.2
SD	6.4	15.6	2.0	7.2

Table D.2

Raw Data

Conventional Shoe

EFC	VO2	SLC	SFC	FHC	HAC	KAC	AA	HD	SW	HO
0.149	47.3	0.80	180	0.34	31.2	21	-7.6	0.21	9.8	4
0.128	54.9	0.92	168	0.39	20.5	21.6	-26.6	0.18	11.5	15
0.129	53.9	0.99	164	0.18	9.6	5.6	6.8	0.13	9.4	11
0.160	44.5	1.00	161	0.39	33.1	15.3	-8.5	0.23	12	12
0.153	45.2	1.00	160	0.25	49.3	21.6	-7.7	0.16	11	15
0.139	52.5	0.88	174	0.21	51.6	25.5	-13.8	0.13	12.4	14
0.133	48.6	0.80	187	0.24	31.2	25.1	-1.5	0.1	11.6	12
0.144	48.4	0.93	173	0.2	22.1	7.3	-12.3	0.12	12	12
0.141	49.7	0.79	183	0.27	35.7	16.5	13.4	0.08	13.5	12
0.148	47.6	0.77	183	0.39	0.39	16.8	2.5	0.24	12.1	12
0.1423	49.3	0.89	173.	0.286	28.469	17.63	-5.53	0.15	11.5	11.9

Vibram Shoe

EFV	VO2V	SLV	SFV	F	HAV	KAV	AA	HD	SW	HO
0.155	45.6	0.86	177	0.	42.5	23.3	1.9	0.21	5.8	0
0.135	51.9	0.94	170	0.	18.8	21.6	-14.2	0.18	6.5	0
0.131	52.6	1.00	161	0.	6.5	6.7	14.3	0.14	5.8	0
0.156	45.8	0.96	166	0.	22.6	20.9	-7.6	0.22	6.5	0
0.159	43.5	0.96	171	0.	25.9	24.3	-1	0.17	5.3	0
0.136	49.4	0.97	169	0.	40.8	25.5	3.5	0.13	5.8	0
0.138	49.1	0.76	198	0.	38.4	25.1	7.1	0.13	7.1	0
0.150	46.4	0.89	181	0.	20.7	13.6	-4.4	0.11	5.3	0
0.135	51.4	0.79	181	0.	38.6	21.9	16.2	0.1	6.5	0
0.144	47.5	0.89	175	0.	0.4	46.6	17.6	0.22	6.5	0
0.144	48.3	0.90	174.9	0.	25.52	22.95	3.34	0.16	6.11	

Note: EF = efficiency; SL = stride length; SF = stride frequency; FH = foot to hip distance at foot strike; HA = hip angle; KA = knee angle; AA = ankle angle; HD = hip displacement; SW = shoe weight; HO = heel offset

Table D.3

Delta Efficiency Conventional Shoes vs. Vibram Five Finger Shoes

	Conventional			Vibram		
	6.0 mi/hr	7.5 mi/hr	9.0 mi/hr	6.0 mi/hr	7.5 mi/hr	9.0 mi/hr
	0.148	0.145	0.149	0.142	0.136	0.155
	0.129	0.128	0.128	0.139	0.130	0.135
	0.116	0.126	0.129	0.115	0.160	0.131
	0.154	0.160	0.160	0.154	0.160	0.156
	0.159	0.157	0.153	0.160	0.159	0.159
	0.144	0.144	0.139	0.140	0.149	0.136
	0.134	0.133	0.133	0.144	0.141	0.138
	0.138	0.145	0.144	0.142	0.152	0.150
	0.144	0.141	0.141	0.150	0.144	0.135
	0.141	0.149	0.148	0.141	0.144	0.144
Mean	0.141	0.143	0.142	0.143	0.147	0.144
SD	0.012	0.011	0.011	0.012	0.010	0.010
Group Mean			0.142			0.145

Table D. 4

Metabolic Economy: Conventional Shoes vs. Vibram Five Finger Shoes, *(VO_2 ml•kg-1min-1)*

	Conventional Shoes			Vibram Five Fingers		
	6.0 mi/hr	7.5 mi/hr	9.0 mi/hr	6.0 mi/hr	7.5 mi/hr	9.0 mi/hr
	32.8	41.2	47.3	33.7	40.5	45.6
	36.8	46.2	54.9	33.8	43.3	51.9
	40.7	46.5	53.9	41.0	44.7	52.6
	30.6	36.7	44.5	31.5	37.5	45.8
	30	37.7	45.2	29.4	36.5	43.5
	33.9	42.0	52.5	32.5	38.9	49.4
	31.8	39.5	48.6	32.9	38.4	49.1
	34.6	40.7	48.4	33.8	39.5	46.4
	32.9	41.6	49.7	31.1	40.6	51.4
	34.2	40.2	47.6	33.7	40.5	47.5
Mean	33.8	41.2	49.3	33.3	40.0	48.3
SD	3.1	3.2	3.5	3.1	2.5	3.0
Group Mean			41.4			40.6

APPENDIX E

IRB Approval

SONOMA STATE UNIVERSITY—INSTITUTIONAL REVIEW BOARD FOR THE RIGHTS OF HUMAN SUBJECTS

Application for Approval of Research Involving Human Subjects

This application is designed to fulfill the responsibilities of Sonoma State University relative to the Code of Federal Regulations, Title 45, Part 46, regarding research involving human subjects. Failure to comply with the policies and procedures referenced in this application (1) may cause individuals to incur personal liability for negligence and harm; (2) may cause the University to lose federal funding, prevent individuals from applying for or receiving federal research funds, and prevent the University from engaging in research; and (3) will be viewed by SSU as a violation of university policies and procedures and will result in appropriate administrative action.

All research involving the use of human subjects conducted by SSU faculty, staff, or students —or sponsored in part or whole by SSU— must be reviewed and approved by the University's Institutional Review Board (IRB) for the Rights of Human Subjects prior to the start of the project and then must be conducted in full compliance with University policies and procedures. **It is the responsibility of the principal investigator to refer to the IRB any project involving human subjects, even if the subjects are not considered to be "at risk."** This includes research conducted in conjunction with classroom assignments that will be published or shared, as well as student dissertation or thesis. It also includes all interviews, questionnaires, surveys, observations, educational tests, and secondary analyses of previously collected data that will be incorporated into published research or other public presentation. Such projects may be undertaken only after appropriate approval and may be continued only so long as that approval remains in effect. Changes in a project, or continuation of the project following adverse or untoward occurrences during the project, are also subject to review and approval.

Research intended solely for classroom use (with no possibility of further disclosure or publication) and conference/workshop evaluation surveys do **not** require IRB review.

Submit applications to: Sonoma State University, Institutional Review Board –Stevenson 1024, 1801 East Cotati Ave., Rohnert Park, CA 94928

If you have any questions, contact the Office of Research and Sponsored Programs at 664-2448 or email *irb@sonoma.edu*

NOTE*: Your complete application is* ***due one month prior*** *to the start of your research. It should include:*

- *Pages 1-3 of this application plus additional pages for the Protocol Requirements (page 3) as needed.*
- *A copy of your written informed consent form OR a request for waiver of written informed consent with a copy of the oral text you intend to use to inform your subjects of the points listed on the Checklist of Informed Consent (see http://www.sonoma.edu/aa/orsp/human_subjects.shtml for a sample consent form and checklist).*

This form is designed to be completed on a computer using Microsoft Word. Complete all applicable gray form fields and check boxes. See http://www.sonoma.edu/aa/orsp/human_subjects.shtml for a version suitable for completion by hand or typewriter

Your signature below certifies that:

- You have read this 6-page packet and understand your responsibilities and liabilities as a principal investigator.
- You have reviewed the University's policies and procedures on research involving human subjects and will ensure your research is conducted in full compliance. Copies of the policies and procedures are available from the Office of Research and Sponsored Programs (ORSP) in Stevenson Hall, Room 1024. The information is also posted on the ORSP website at http://www.sonoma.edu/aa/orsp/ .
- You have completed Module 2 (Investigator Responsibilities & Informed Consent) of the Human Subject Assurance Training provided online by the Office of Human Research Protections at: http://137.187.172.153/CBTs/Assurance/login.asp
- You, your spouse, or your dependent children have no financial interest in your project that will or may be reasonably expected to bias the design, conduct, or reporting of your research.

Signature of Principal Investigator:______________________________ Date: ____________

Title of Project: Efficiency of treadmill running under two footwear conditions : Vibram Five Fingers shoes versus conventional running shoes

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Co-Investigator(s): Jordan Smith

For student investigators only:

Please print or type name of professor or faculty advisor: Lauren Morimoto

Signature of professor or faculty advisor: ____________________ Title or Academic Status: PhD

Department clearance: ______________________________________ Date: __________