THE EFFECT OF MANIPULATING VERTICAL MOTION ON RUNNING ECONOMY

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ABSTRACT

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While several biomechanical factors have been identified as key determinants of running economy (i.e. metabolic cost), the influence of individual mechanical factors such as center of mass vertical motion (ΔCoM_z) remains unclear. The purpose of this study was to determine how manipulating ΔCoM_z effects running economy. Twelve runners used a visual biofeedback system to control their ΔCoM_z during running as we measured the metabolic, kinematic, and muscle activation responses to the different levels of ΔCoM_z. Running economy was strongly correlated to ΔCoM_z and was optimized at an intermediate center of mass vertical motion of 6-8cm. Changes in ΔCoM_z were associated with changes in ground contact time (TC), stride length (SL), and peak knee flexion angle, as well as the magnitude of Biceps Femoris (BF), Vastus Lateralis (VL), and Tibialis Anterior (TA) muscle activation.

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INTRODUCTION

The number of marathon runners has been increasing over the past several years, peaking in 2016 with 507,600 USA runners (Running USA, 2017). Not all of these runners are competitive, but most people who run want to improve their performance. As overuse injuries affect up to 70% of runners during their running career, improved running efficiency may help to reduce these injuries due to decreased fatigue (Hreljac, Marshall, & Hume, 2000). Running economy (RE) is a key determinant of running performance; especially over longer distances where more economical running patterns could make a big difference in performance (Barnes & Kilding, 2015; Hreljac et al., 2000; Moore, 2016). By understanding the relation between running mechanics and running economy, coaches and athletes will be able to make informed decisions on how to improve running performance.

Running economy is a modifiable performance measure defined as the rate that O_2 is consumed at a standardized running speed (L. Conley & Krahenbuhl, 1980). RE can be a better indicator of performance than VO_{2max} when runners are at similar performance levels (Anderson, 1996; Morgan, Baldini, Martin, & Kohrt, 1989). An individual's running economy is believed to be influenced by several key biomechanical factors including: stride length, stride frequency, ground contact time, the amount of and distribution of body mass, and the vertical motion of the body during a stride (ΔCoM_z) (Barnes & Kilding, 2015). However, there currently is no biomechanical pattern of movement that is considered to be the most economical running technique (Barnes &

Kilding, 2015). Some of these factors such as body weight, stride frequency, stride length, and ground contact time are well defined, and their relationship to running economy is well established. However, the effect of whole-body vertical motion on running economy is not well understood. Understanding the impact that ΔCoM_z has on running economy could help to improve a runner's mechanics and contribute to improved performance and decreased risk of overuse injuries.

Movement phases in running are typically defined in relation to the gait cycle. The gait cycle begins when one foot makes contact with the ground, and ends when the same foot makes contact with the ground again. During the gait cycle, the period of time where the foot is in contact with the ground is called the stance phase, and the period of time where the foot is in the air is called the swing phase. In running there is a period, called double float, when both feet are simultaneously off of the ground. The stance phase can be chronologically broken down into the braking and the propulsive phases (Novacheck, 1998). The absolute height of the center of mass (CoM) does not remain constant for the entire gait cycle. It reaches its highest point during double float and its lowest point at midstance. ΔCoM_z is considered a key determinant of the characteristic spring-mass behavior in running.

The spring mass model is currently considered to be the most accurate representation of human running. In this model, the runner's leg acts as the spring during the stance phase by storing and releasing Elastic Potential Energy (EPE) in the muscles, tendons, and ligaments of the legs (Farley, Glasheen, & McMahon, 1993). The stored elastic energy is converted to gravitational potential energy (GPE) and kinetic energy

(KE) as the body is lifted and accelerated, respectively. During the double float phase, the body's CoM is at its highest point and carries the most gravitational potential energy. GPE and KE are then re-stored as EPE during the next stance phase when the CoM is at its lowest point during midstance. Therefore, the storage and return of elastic potential energy is made possible, in part, by the change of the height of the body's CoM. Theoretically, this exchanging of GPE, KE, and EPE allow for mechanical energy to be conserved during running, resulting in a lower metabolic cost and better running economy (Saunders, Pyne, Telford, & Hawley, 2004).

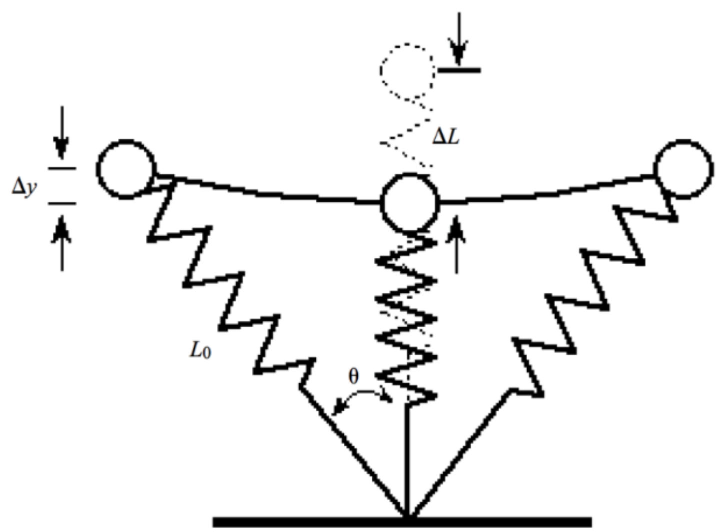

Figure 1: A representation of the spring mass model, where delta L is the change in height of the CoM and the spring is representative of a human leg during the stance phase of running (Saunders et al., 2004).

In the spring mass model, the runner's leg acts as the spring. When forces act on the body during running the amount of compression or extension the leg spring undergoes depends upon on the stiffness of the leg spring. A more stiff leg spring will be less compliant than a less stiff leg spring. Runners have been shown to be able to modify their leg stiffness between different terrain types, allowing the mechanics of their gait to remain relatively unchanged regardless of the running surface (C. T. Farley, Blickhan, Saito, & Taylor, 1991; Ferris, Liang, & Farley, 1999; Ferris, Louie, & Farley, 1998). Runner's leg stiffness during the stance phase controls the vertical motion of the center of mass (McMahon & Cheng, 1990). As leg stiffness increases, vertical motion of the CoM decreases, stride frequency increases, and foot-ground contact time decreases (Claire T. Farley & González, 1996).

Ground contact time (T_c) is a known predictor of running economy (Kram & Taylor, 1990; Morin, Samozino, Zameziati, & Belli, 2007). Short ground contact times are linked to poor running economy as the body needs to generate force more quickly (Morin et al., 2007, Kram & Taylor, 1990) and thus uses more inefficient muscle fibers to quickly generate force (Chang & Kram, 1999; Heise & Martin, 2001; Roberts, Kram, Weyand, & Taylor, 1998). This inverse relationship between stance time and aerobic demand occurs regardless of changes in weight and mass (Kram & Taylor, 1990). Thus, having shorter stance times (i.e. shorter T_c) that require a greater contribution of faster but less efficient muscle fibers during running is believed to negatively impact running economy (Chang & Kram, 1999, Heise & Martin, 2001, Roberts et al., 1998).

Oscillating systems, such as the spring mass model of running, have a resonant frequency that is characterized as the ideal frequency for the system. The resonant frequency is the frequency (Hz) that a system vibrates at after a mechanical trigger (Saunders et al., 2004). In running, a way to modulate the frequency that the system oscillates at is by changing stride frequency. Well trained runners are extraordinarily adept at selecting their optimum stride frequency and stride length; changes over 3% of their self-selected stride frequency and stride length have been shown to be detrimental to running economy(P. R. Cavanagh & Williams, 1982; Williams & Cavanagh, 1987). When calculated using a quadratic fit line from their experimental data, RE is optimized when stride length is about 3% shorter than preferred (Connick & Li, 2014). In addition, changes in stride frequency led to changes in the timing of muscle activation; increased stride frequency led to earlier activation of biceps femoris and vastus lateralis (Connick & Li, 2014). Runners optimize RE at a stride length that is slightly shorter than preferred (Connick & Li, 2014). It has been found that elite runners have a higher stride frequency and slightly lower levels of vertical oscillation than good runners (Peter R. Cavanagh, Pollock, & Landa, 1977).

Runners typically select a stride frequency that minimizes internal and external work (Cavagna et al., 1988). Internal work primarily refers to the work required to move the limbs relative to the CoM, whereas the external work is work required to lift and accelerate the whole body CoM during running(Lieberman, Warrener, Wang, & Castillo, 2015). Increases in stride frequency are correlated with less vertical motion (Lieberman et al., 2015).

As stride frequency increases, so does internal work. As vertical motion of the CoM decreases, external work decreases. Reducing VM has been theorized to decrease metabolic cost of both walking and running (Saunders et al., 2004). Specifically, in running, it has been suggested that reducing ΔCoM_z decreases the metabolic cost of running by reducing the amount of external work that has to be performed to move and accelerate the CoM (Saunders et al., 2004).

Ground reaction forces (GRF) are forces acting on the runner that are equal and opposite to the forces that a runner exerts on the ground. The ground reaction force in running has both a horizontal (forward/aft) and a vertical component. The horizontal GRF are associated with the cost of braking and forward propulsion whereas the vertical GRF are associated with the cost of supporting body weight and accelerating the CoM vertically (Chang & Kram, 1999). The cost of supporting weight and the rate of force generation is considered by many researchers to be the primary determinants of the metabolic cost of running (Kram & Taylor, 1990; Roberts et al., 1998). It has been estimated that the cost of supporting weight while running may account for as much as 74% of the total energy cost of running (Teunissen, Grabowski, & Kram, 2007) and is directly proportional to magnitude and rate of the ground reaction forces (Kram & Taylor, 1990; Roberts et al., 1998; Teunissen et al., 2007). The sum of all ground reaction forces, as well as the total vertical impulse (Vertical GRF X Time), have also been strongly correlated with running economy across a range of speeds (Heise & Martin, 2001). Large ground reaction forces are correlated with poor running economy(Støren, Helgerud, & Hoff, 2011). Moreover, increases in total vertical impulse have been associated with higher levels of muscle activation and likely explain why running economy is reduced with an increase in total vertical impulse (Heise & Martin, 2001).

Changes in ΔCoM_z during running have been correlated to peak vertical GRF and consequently may strongly influence running economy (Williams & Cavanagh, 1987).

The magnitude and direction of GRF are determined by the acceleration and position of a runner's CoM (Novacheck, 1998). Thus, by reducing ΔCoM_z, a runner may decrease the peak vertical GRF and reduce the energetic cost of running (Heise & Martin, 2001).

Although prior studies have looked at how changes in vertical motion affect economy in walking (Ortega & Farley, 2005), very few studies have investigated the relationship between ΔCoM_z and the metabolic cost of running. In some of these studies, vertical motion has been identified as a covariate that changes with the primary mechanical variable believed to influence running economy (Cavagna, Franzetti, Heglund, & Willems, 1988; Peter R. Cavanagh et al., 1977; C. T. Farley et al., 1991), or lower levels of vertical motion occurring in elite runners than recreational runners (Peter R. Cavanagh et al., 1977) More recently, a comprehensive observational study related kinematic variables to runners' best time and metabolic cost of running. They found that there is a large amount of variation in the magnitude of vertical motion between different runners and that the differences in vertical motion of the pelvis during ground contact is strongly correlated with both performance measures (Folland, Allen, Black, Handsaker, & Forrester, 2017). In fact, Folland et al. (2017) found that vertical motion explained 28% of the variation in metabolic cost. In a different study looking at gait manipulations in female distance runners, exaggerated levels of vertical motion were correlated with an increased cost of transport (Wayland, Caputo, & Morgan, 2008). Despite the evidence suggesting a relation between vertical CoM motion and running economy, there are no studies that directly manipulate and quantify changes in vertical CoM motion and how those changes relate to running economy.

At this time, the understanding of how the mechanics of running affects the metabolic cost of running is incomplete. In particular, there is a significant gap in understanding how changes in the amount of vertical motion over the course of the gait cycle influences running economy. Therefore, the purpose of this study is to observe how manipulating vertical motion effects running economy, related kinematic variables, and muscle activation.

METHODS

Participants

Twelve participants (7 males, 5 females, 25.5±5 yo, 73±8kg, 176±5cm) who ran an average of 25±10 miles a week, and had an average 5k time of 21±4 min, participated in this experiment. All participants had treadmill running experience, were free of any neurological disease, cardiovascular disease, major illnesses, and lower body injury for the 6 months prior to the study. Participants were recruited from Humboldt State University and the Humboldt County community. All participants provided written informed consent and the study was approved by the Humboldt State University Institutional Review Board.

Experimental Design

Each participant completed one familiarization and one experimental session. For both the familiarization and experimental sessions, participants ran on a motorized treadmill (Trackmaster TMX425C, Full Vision Inc., Newton, KS) at a speed of 6mph (2.68 m/s) for a minimum of six minutes under each of 5 randomized experimental conditions. The experimental conditions included running with 1) preferred (100%) vertical CoM oscillation, 2) 150% of preferred vertical CoM oscillation, 3) 125% of preferred vertical CoM oscillation 4) 50% of preferred vertical CoM oscillation, and 5) 75% vertical CoM oscillation. Participants were given a minimum of 5 minutes rest between trials. During the experiment, HR was taken (Polar, something) to ensure that participants were fully rested between trials.

In the familiarization session, we oriented each participant to the study design, obtained informed consent, took anthropomorphic measures to specify kinematic data, and familiarized the participant to treadmill running while using a biofeedback system to control ΔCoM_z.

In the experimental session, participants performed six trials including one standing metabolic trial and the five experimental ΔCoM_z running conditions. Each trial was 6 minutes in duration with a minimum of 5 minutes rest between trials. For each experimental trial, we measured full body kinematics using digital motion capture, leg muscle activation using EMG, and metabolic cost using indirect calorimetry. The experimental session occurred a minimum of two days following the familiarization session or any other lower body workout to reduce the influence of fatigue.

CoM Vertical Motion Biofeedback

Participants used live video feedback of a target marker placed on their trunk at T10 to control the vertical motion of their body during the experimental running trials. The position of the target marker was projected in real-time on a 23-inch video monitor placed 1 meter in front of the participant. Participants were not told to manipulate their gait in any specific way other than to maintain each amount of prescribed ΔCoM_z throughout the trial using the biofeedback system.

Measurements

Metabolic Cost was measured using an open circuit gas ($\dot{V}CO_2$ + $\dot{V}O_2$) analysis (ParvoMedics, Inc., Sandy, UT) during all trials. We quantified the average metabolic cost for the last two minutes of each trial to help ensure participants achieved submaximal metabolic steady-state. The standing metabolic rate was subtracted from the gross metabolic cost to calculate the net metabolic cost normalized to body mass ($J*kg^{-1}*s^{-1}$).

Kinematics were collected using a nine-camera 3D motion capture system (200 fields/s, Vicon Nexus, Centennial, CO). Kinematic data was collected for 10 strides during the last 2 minutes of each trial. For data collection, we used a cluster marker set that is based on the calibrated anatomical systems technique (CAST) using six degrees of freedom (Cappozzo, Catani, Della Croce, & Leardini, 1995). A total of 48 independent 14mm reflective markers were on the participant during data collection. This data was used to calculate the vertical displacement of the CoM, temporal-spatial gait characteristics such as: cadence, stride length, and time of ground contact (T_c), and lower body joint kinematics. ΔCoM_z was calculated as the difference between the absolute maximum height of the CoM from the absolute minimum height of the CoM during the course of a gait cycle.

Raw marker data was filtered using a fourth order zero-lag Butterworth low-pass filter with a cut-off frequency of 10 Hertz, and processed in using a custom Visual 3D pipeline (C-Motion, Germantown, MD).

Muscle Activation was determined via surface electromyography (EMG) sampled at 2000 Hz. Surface electrodes (Trigno, Delsys Incorporated, Boston, MA) were placed on five muscles on the left leg: Tibialis Anterior (TA), Medial Gastrocnemius (MG), Soleus (S), Vastus Lateralis (VL), and Gluteus Maximus (GM). EMG data was only collected on one leg under the assumption that participants have a symmetrical gait. We verified the electrode position and signal quality by visually inspecting EMG signal while the participant performs a maximum voluntary contraction. Data was collected for 30 seconds during the last 2 minutes of the trial, concurrently with kinematic data. The recorded signals were passed through a band-pass filter (20-450Hz) by the Delsys hardware before analysis. We full wave rectified the raw EMG signal and calculated the normalized root mean square (40ms) using a Visual 3D analysis program (Germantown, MD). This processed EMG amplitude was normalized relative to peak amplitude during the baseline trial. We calculated the average processed EMG signal magnitude across the entire gait cycle, from initial contact until toe-off, as well as in 10% increments across the entire gait cycle.

Statistical Analysis

We ran a repeated measures ANOVA to compare metabolic, kinematic, and EMG data from the experimental conditions to $\Delta CoM_{z,pref}$ trial for all participants. If the main effect of vertical motion was found, a Bonferroni post-hoc analysis were run to determine which experimental conditions differ significantly from ΔCoM_z. All tests were run at a significance level $p < 0.05$.

To better understand the influence of significant kinematic variables on metabolic cost, we performed a post-hoc stepwise regression analysis of the data. The relationships between ΔCoM_z (cm), ground contact time (s), stride length (m), peak knee flexion angle (deg), and metabolic cost normalized to bodyweight ($J*kg^{-1}*s^{-1}$)was assessed as bivariate relationships with independent Pearson's product-moment correlations. P values were corrected using the Benjamini-Hochberg procedure, with a 5% false detection rate and an adjusted significance of $p < .005$. Variables were excluded from the regression if the variance inflation factor was over 2.5. The average variance inflation factor for the included variables was 1.4.

Operational Definitions

1. Stride Frequency – the number of strides per second (Hz)
2. Stride Length – the length (m) between a foot strike and the ipsilateral foot strike
3. Vertical Motion – vertical displacement of the COM through the gait cycle
4. Ground Contact Time (T_c) – the amount of time that the foot is in contact with the ground
5. Leg Stiffness – a measure of the spring characteristics of the leg, used to characterize leg function in bouncing gaits
6. Ground Reaction Force – the force that is exerted on the runner by the ground due to forces that the runner exerts onto the ground

Assumptions

1. All participants will accurately report their running experience and medical history (see Appendix A).

2. All participants will have a symmetrical running gait for both kinematics and muscle activation.
3. All participants will be able to maintain the prescribed CoM vertical oscillation for the entirety of each experimental trial.
4. All participants will follow pre-exercise instruction (see appendix B) prior to participation in the study.

Limitations

1. Subjects self-reported activity level and running experience.
2. Subjects may have had a difficult time maintaining the prescribed ΔCoM_z for the duration of the experimental trial.
3. During experimental trials, the prescribed ΔCoM_z was normalized to the subject (% of preferred vertical oscillation) rather than an absolute value (e.g. 3 cm).

Delimitations

1. One speed (6mph) was used for all trials.
2. Muscle activation was collected on one leg of the subject.
3. Participants only included men and women age all 18-35 years, who ran at least three times a week for a minimum of 30 minutes, and who were free of lower limb injuries for 6 months leading up to testing.
4. Only four levels ΔCoM_z were be tested (preferred, 50% of preferred, 75% of preferred, 125% of preferred, 150% of preferred).

RESULTS

Metabolic Cost

The purpose of this study was to determine the effect of systematically manipulating CoM vertical motion on RE, kinematics, and muscle activation. In support of our hypothesis, changes in ΔCoM_z led to changes in the net metabolic cost of running (Figure 1). Specifically, subjects consumed the least metabolic energy at the intermediate $\Delta CoM_{z,pref}$ (8 ± 0.43 cm) and consumed 12% and 27% more at the 50% and 150% of $\Delta CoM_{z,pref}$ respectively (p=.04).

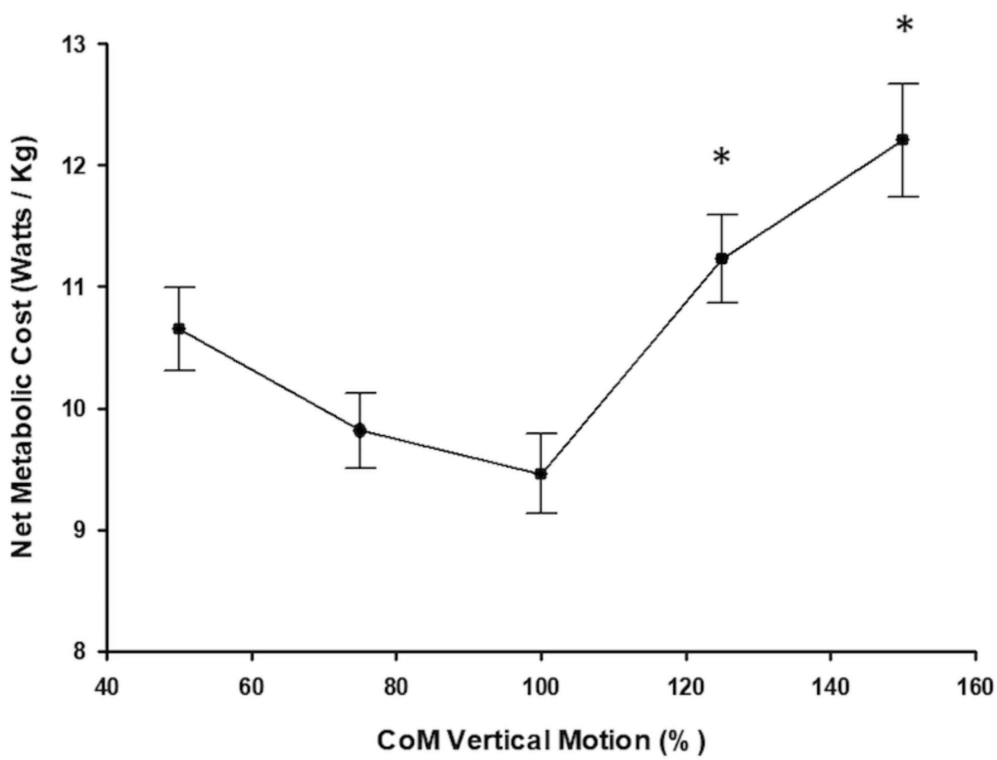

Figure 2: Net metabolic power (W/kg) plotted as a function of the percentage of ΔCoMz,pref. Error bars represent the standard error of the mean (SEM). When ΔCoMz

was increased or decreased relative to ΔCoMz,pref, metabolic cost of running increased. *Significant

While ΔCoM_z was prescribed relative to each subject's $\Delta CoM_{z,pref}$, regression analysis showed a moderate curvilinear relation between RE and CoM vertical motion in cm (Figure 2) such that ΔCoM_z accounted for 42% of the variance in metabolic cost (R^2 = .487).

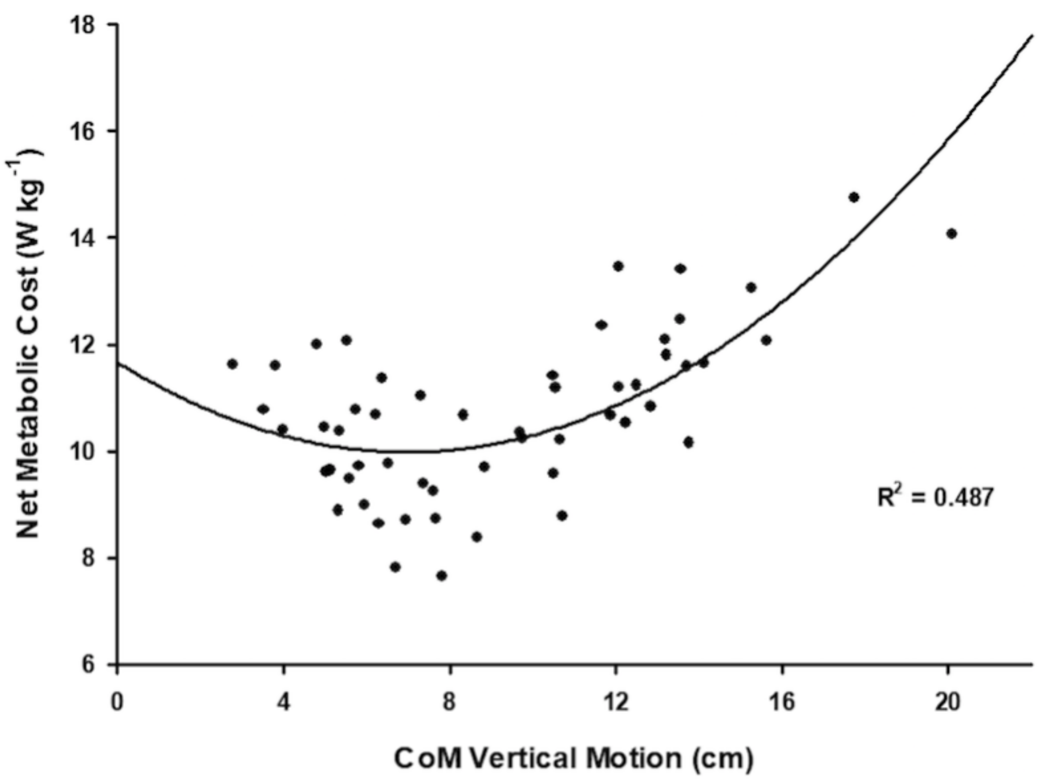

Figure 3: Relation between net metabolic cost (W/kg) and CoM vertical motion (cm) during running. Line is 2nd order least square regression: 346.04 X2- 48.316X + 11.667, F(2,52) = 29.60, R^2 = .487, P<.0001. While metabolic cost is minimized at intermediate

$\Delta CoMz$ of ~6-8 cm, a 69% increase from $\Delta CoM_{z,pref}$ increased metabolic cost by 29% whereas a 43% decrease from $\Delta CoM_{z,pref}$ increased metabolic cost by 13%.

Kinematics

Participants relied on visual biofeedback to maintain prescribed levels of ΔCoM_z during each trial. While ΔCoM_z was prescribed at levels of 50%, 75%, 100%, 125%, and 150% of $\Delta CoM_{z,pref}$, the measured ΔCoM_z differed from prescribed by an average of 9% with the greatest difference at $\Delta CoM_{z,150}$ where the actual ΔCoM_z equaled 170% (Table 1). Despite this discrepancy, figures and results refer to the prescribed percentage of $\Delta CoM_{z,pref}$ for consistency.

Table 1 Mean values of vertical oscillation (cm) ± SEM, converted into percentages (N=12).

Prescribed % of $\Delta CoM_{z,pref}$	Vertical CoM Displacement (cm)	Actual % of $\Delta CoM_{z,pref}$
50 %	4.8 (± 0.3)	42 ± X %
75 %	6.4 (± 0.3)	77 ± X %
100 %	8.3 (± 0.4)	100 ± X %
125 %	12.2 (± 0.8)	132 ± X %
150 %	14.1 (± 0.4)	170 ± X %

SpatioTemporal Variables

Changes in CoM vertical motion led to significant changes in ground contact time (s), stride length (m), and stride frequency (Hz) (Table 2). Across the range of ΔCoM_z, ground contact time increased by an average of 6.3% with each 25% increase from $\Delta CoM_{z,50}$ ($P<.0001$). Adding ground contact time to the regression analysis accounted for an additional 16% of the variance in metabolic data, for a total of 58% of the variance explained by ΔCoM_z and T_C (s). Stride length increased by 17% when CoM vertical motion was increased to $\Delta CoM_{z,150}$ from $\Delta CoM_{z,pref}$ (P<.0001), and decreased by 12% when CoM vertical motion was decreased to $\Delta CoM_{z,50}$ (P<.0001). However, stride length did not significantly contribute to the regression model (P>.05). Stride frequency decreased by 14% when CoM vertical motion was increased to $\Delta CoM_{z,150}$ from $\Delta CoM_{z,pref}$ (P<.0001), and increased by 14% when CoM vertical motion was decreased to $\Delta CoM_{z,50}$ (P<.0001). We did not include stride frequency in the regression analysis.

Table 2 Mean values for spatiotemporal variables ± SEM (N=12). P-values given for variables with significant difference from ΔCoMz,pref (P<.05).

Variable	Mean (± SEM)	Significance
Stride Length (m)		p = .002
50%	1.72 (± 0.04)	p < .0001
75%	1.81 (± 0.03)	p < .0001
Preferred (100%)	1.95 (± 0.03)	
125%	2.18 (± 0.03)	p = .001
150%	2.28 (± 0.05)	p < .0001
Stride Frequency (Hz)		p < .0001
50%	1.57 (± 0.04)	p < .0001
75%	1.49 (± 0.03)	p < .0001
Preferred (100%)	1.38 (± 0.02)	
125%	1.23 (± 0.02)	p < .0001
150%	1.18 (± 0.02)	p < .0001
Ground contact time (T_C) (s)		p < .0001
50%	.17 (± 0.01)	p = .009
75%	.19 (± 0.00)	p = .007
Preferred (100%)	.20 (± 0.01)	
125%	.21 (± 0.01)	

Variable	Mean (± SEM)	Significance
150%	.22 (± 0.01)	

Joint Angles

We measured average and peak joint angles for the hip, knee, and ankle during stance phase for all conditions (Table 3). Of those, only peak knee flexion angle changed significantly from $\Delta CoM_{z,pref}$, increasing by 5.2 degrees at $\Delta CoM_{z,150}$ (P=.014), and decreasing by 4.4 degrees at $\Delta CoM_{z,50}$ (P=.01). However, peak knee flexion angle did not significantly contribute to the regression analysis (P>.05).

Table 3 Mean values for peak joint flexion during stance phase ± SEM (N=12). P-values given for variables with significant difference from ΔCoMz,pref (P<.05).

Kinematic Variable	Mean (± SEM)	Significance
Peak Hip Flexion (deg)		P=.098
50%	30.07 (± 2.77)	
75%	29.78 (± 2.16)	
100%	30.45 (± 2.03)	
125%	32.98 (± 2.13)	
150%	33.18 (± 3.00)	
Peak Knee Flexion (deg)		P<.001
50%	25.25 (± 1.00)	P=.014
75%	22.30 (± 0.67)	
100%	19.91 (± 1.10)	
125%	15.57 (± 0.61)	P = .007
150%	15.25 (± 1.40)	P = .307
Peak Ankle Flexion (deg)		
50%	20.25 (± 0.92)	
75%	20.45 (± 0.75)	
100%	21.51 (± 0.60)	
125%	21.00 (± 0.74)	
150%	20.96 (± 0.93)	

Muscle Activation

Changes in CoM vertical motion influenced muscle activation (MA) patterns in the upper and lower leg (Figures 3 & 4). As CoM vertical motion decreased relative to $\Delta CoM_{z,pref}$, muscle activation increased in the Biceps Femoris (P<.001), Vastus Lateralis (p = .004), Tibialis Anterior (P<.001), and Soleus (P=.039). Additionally, TA activation decreased as CoM vertical motion increased relative to $\Delta CoM_{z,pref}$ (P=.002). There were no significant muscle activation changes in the Gluteus Maximus and the Medial Gastrocnemius.

Post hoc comparisons revealed that as $\Delta CoM_{z,pref}$ decreased to $\Delta CoM_{z,75}$ and $\Delta CoM_{z,50}$, Biceps Femoris activation increased by 54% (P=.002) and 78% (P=.003), respectively. Vastus Lateralis activation increased by 56% from $\Delta CoM_{z,pref}$ to $\Delta CoM_{z,50}$ (P=.011). Soleus activation increased by 32% from $\Delta CoM_{z,pref}$ to $\Delta CoM_{z,50}$ (P=.025). Tibialis Anterior activation increased 27% from $\Delta CoM_{z,pref}$ to $\Delta CoM_{z,50}$ (P=.047), and decreased by 35% with every prescribed increase from $\Delta CoM_{z,pref}$ (P=.002).

To further understand how MA changed during the gait cycle, we analyzed the average activation of each muscle in 10% increments across the gait cycle. The increases in BF and TA muscle activity primarily occurred during the first 30% of the gait cycle. Additionally, BF activity decreased by and average of 10% from $\Delta CoM_{z,pref}$ between 30-

40% of the gait cycle.

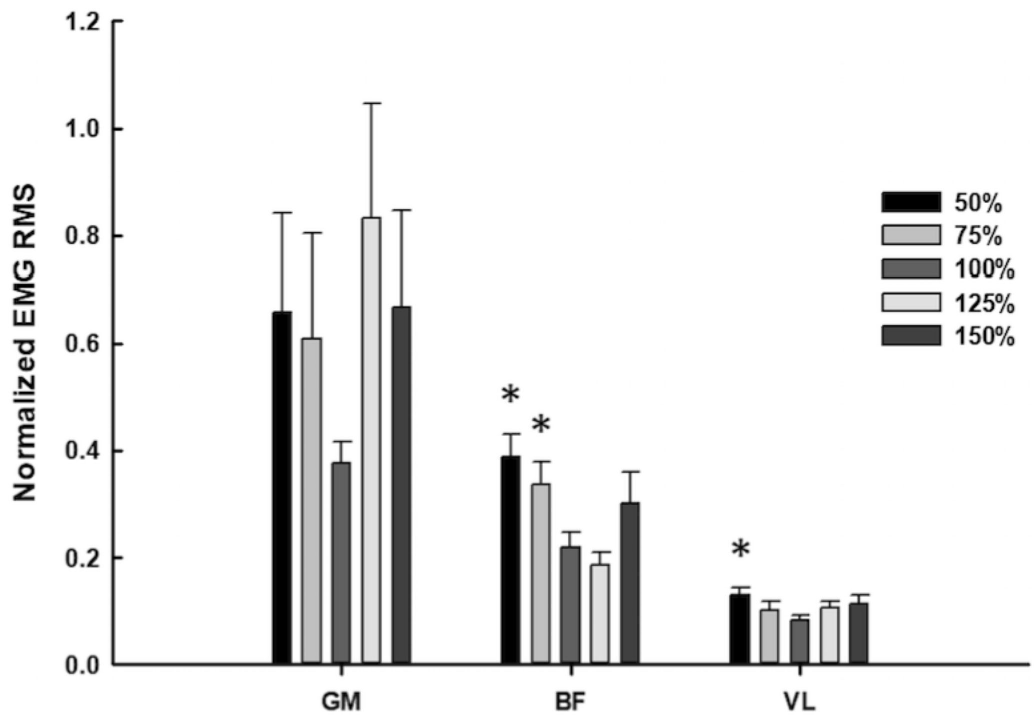

Figure 4: Mean normalized EMG RMS signals of the upper leg: Gluteus Maximus (GM), Biceps Femoris (BF), and Vastus Lateralis (VL), during the stance phase. Asterisk (*) indicates significant differences from ΔCoMz.pref for BF (P=.007) and VL (P=.004).

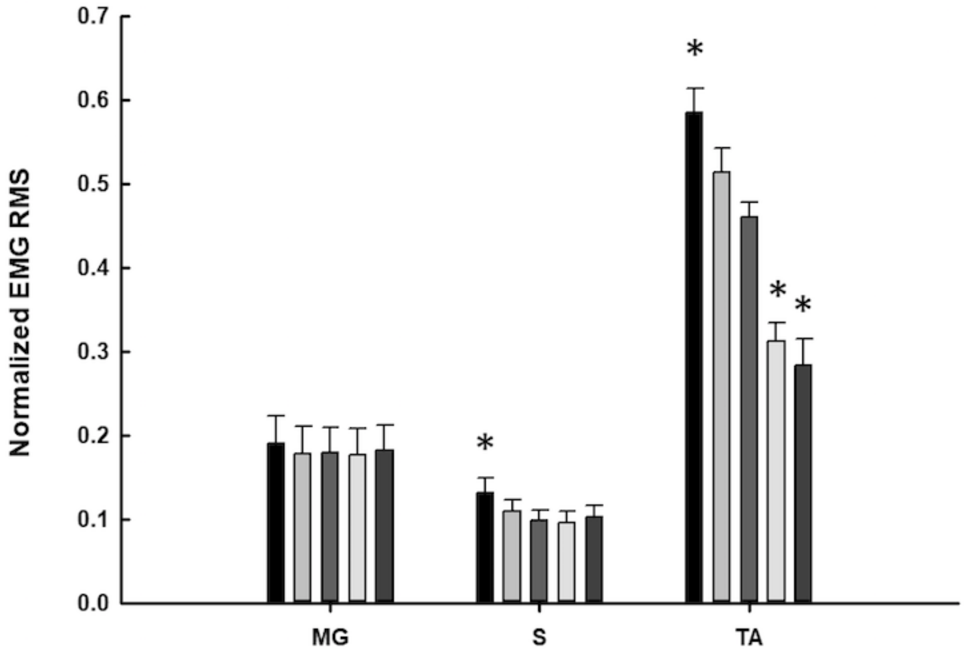

Figure 5: Mean normalized EMG RMS signals of the lower leg: Medial Gastrocnemius (MG), Soleus (SOL), and Tibialis Anterior (TA), during the stance phase. Asterisk (*) indicates significant differences from ΔCoMz,pref (P<.05).

DISCUSSION

The present study aimed to determine the relation between center of mass vertical motion and running economy. We initially hypothesized that running economy would improve as ΔCoM_z was reduced. We reject our initial hypothesis because the participants optimized running economy at or slightly below $\Delta CoM_{z,pref}$, and substantial changes (increases or decreases) in ΔCoM_z relative to $\Delta CoM_{z,pref}$ impaired running economy. The results of this study also show that ΔCoM_z accounted for 42% of the variance in running economy. In support of our secondary hypothesis, we found that increasing ΔCoM_z increased ground contact time and that changes in T_C accounted for an additional 16% of the variance in running economy. Changes in ΔCoM_z were also associated with significant changes in stride length, peak knee flexion angle, and muscle activation. Of all of the kinematic variables, ΔCoM_z was the strongest predictor of metabolic cost; supporting the hypothesis that ΔCoM_z is a key biomechanical predictor of RE.

In previous observational studies, the average measured $\Delta CoM_{z,pref}$ in a complete stride ranged from 5.2 cm (Folland et al., 2017) to 9.52 cm (Tartaruga et al., 2012). We found an intermediate value of 8.3 cm for $\Delta CoM_{z,pref}$. This variation in measured $\Delta CoM_{z,pref}$ may be explained by methodological differences. Seeing as other kinematic variables, such as ground contact time and stride length, are known to be speed dependent, it follows that speed may influence a runner's $\Delta CoM_{z,pref}$. However, this has yet to be systematically evaluated. The speeds tested ranges from 2.68 m/s in the current study to 2.7-3.3m/s (Folland et al., 2017), and up to 4.4 m/s (Tartaruga et al., 2012). The differences in methodology may also help to explain the variability in $\Delta CoM_{z,pref}$. While Folland et al and the present study used high speed (120 Hz) 3D motion capture to quantify ΔCoM_z, Tartaruga et al used 2D motion capture to determine ΔCoM_z. Moreover, in the study performed by Folland et. al. (2017) utilized more elite runners, who have been shown to use a lower $\Delta CoM_{z,pref}$. Nonetheless, the $\Delta CoM_{z,pref}$ values that we observed are well within the range of $\Delta CoM_{z,pref}$ found in previous studies.

Although slightly low than observed in prior studies, ΔCoM_z accounted for 42% of the variance in running economy in the present study. Using regression analysis to correlate ΔCoM_z with metabolic cost, Tartaruga et al and Folland et al. found that ΔCoM_z accounted for 65% and 53% of the variance in running economy, respectively. The difference between these studies may also be due to the methodological differences mentioned above in addition to the differences in how the researchers calculated ΔCoM_z. In an effort to find the best predictor of running economy, Folland et. al. calculated ΔCoM_z only during the time of ground contact and normalized their values to body height. In post-hoc analysis, we found no change in R^2 when we normalized ΔCoM_z to the height of the runner. It is likely that the small differences in the observed relation between ΔCoM_z and running economy may be related to our method of calculating ΔCoM_z for the whole stride rather than just during ground contact. Despite these methodological differences, all three studies found a moderate to strong correlation between ΔCoM_z and metabolic cost of running, and thus support the hypothesis that ΔCoM_z is a key biomechanical predictor of running economy.

Prior studies have been inconsistent with recommendations for the optimal amount of ΔCoM_z needed for the most efficient running economy. Based off of a predictive model from their observational data, Tartaruga inferred that greater ΔCoM_z would lead to a decrease in metabolic cost. In contrast to Tartaruga et al. model, our results show that a 150% increase from $\Delta CoM_{z,pref}$ lead to an average increase of 27% in metabolic cost. This change in metabolic cost with increasing ΔCoM_z is similar to the 18% increase observed by Wayland et al. (2008) with a four SD increase from $\Delta CoM_{z,pref}$. Notably, Wayland et al. found a wide variety of metabolic responses to increases in $\Delta CoM_{z,pref}$, ranging from an 8-36% increase. This wide range of metabolic responses to perturbations from $\Delta CoM_{z,pref}$ may help to explain the different amounts of variance accounted for by ΔCoM_z noted above. Additionally and in contrast to Tartaruga et al.'s model, Folland et al. (2017) suggests that lower amounts of ΔCoM_z are correlated with better running performance and economy. While our results agree with Folland et al. prediction that metabolic cost increases at ΔCoM_z above preferred, in contrast to Folland et al., we found that metabolic cost increased as ΔCoM_z decreased below 75% of preferred. This difference between Folland et al.'s prediction and our finding may be due to the fact that Folland et al. based their recommendation on observing $\Delta CoM_{z,pref}$ and metabolic cost in different skilled runners, whereby runners with the higher performance level exhibited lower $\Delta CoM_{z,pref}$ than a less skilled recreational runner. Because it was not directly measured by Folland et al., the relation between ΔCoM_z and running economy with each of their participants is unclear. Thus, it is still possible that with-in each runner, running economy is optimized at some intermediate ΔCoM_z.

Changes in internal and external work may be key determinants of the curvilinear relation between ΔCoM_z and running economy. During running the leg muscle consume metabolic energy to perform external mechanical work to lift and accelerate the center of mass and to perform internal mechanical work to swing the legs forward during each stride. As ΔCoM_z increases, the external work required to lift and accelerate the center of mass increases (Saunders et al., 2004). However, as external work increases with greater ΔCoM_z, the internal work required to swing the legs decreases as a result of decreasing stride frequency (Cavagna, Mantovani, Willems, & Musch, 1997). Based on these same relations, reducing ΔCoM_z decreases the amount of external mechanical work performed on the center of mass while increasing internal mechanical work (Cavagna et al., 1997; Saunders et al., 2004). This prior research suggests that there may be a ΔCoM_z whereby the balance of external and internal work required for running and thus metabolic cost is optimized. Based on the relation between mechanical work and metabolic cost, Connick & Li (2014) developed a model that predicts total mechanical work (external + internal) and metabolic cost are optimized at a stride length 2.9% below preferred stride length. While we were not able to measure internal and external work during the running trials, in accordance with this model, when ΔCoM_z was reduced to 75% of preferred, we observed a ~5% decrease in stride length and that metabolic cost was optimized between $\Delta CoM_{z,75}$ and $\Delta CoM_{z,pref}$. These findings support the idea that changes in center of mass vertical motion directly influences the amount of internal and external work required for running and thus running economy. In addition to changes in internal and external work, manipulating ΔCoM_z led to changes in ground contact time and muscle activation patterns that may also help explain the changes seen in metabolic cost.

In accordance with the cost of generating force hypothesis, our study showed that variations in ground contact time were directly related to running economy. Specifically, T_C accounted for 16% of the variance in metabolic cost across the tested range of ΔCoM_z. However, prior studies have found that ground contact time accounts for as much as 70-90% of the variance in metabolic rate across a range of speeds (Kipp, Grabowski, & Kram, 2018; Roberts et al., 1998). The lower correlation between T_C and metabolic cost in the present study may be related to the relatively small changes in T_C across the different conditions observed in this study, with a range of 0.17s to 0.22s from low to high ΔCoM_z. Using the smaller range of T_C observed in the present study and the equation, $0.262(1/T_c) = metabolic\ cost$, created by Roberts et al. (1998), metabolic cost would be predicted to vary by 1.54 to 1.19 W/N due to the changes in T_C related to variations in ΔCoM_z. This predicted change in metabolic cost due to changes in T_C is far smaller than the range metabolic cost observed Roberts et al., 1998. The reason for the small range of metabolic cost may be related to the fact that prior researchers used T_C to account for metabolic differences across a large range of running speeds in which T_C varied more widely; whereas T_C varied to a lesser extent as a result of changing ΔCoM_z, and thus may possibly explain the lower correlation between T_C and running economy in the present study. In order to better understand the independent effects of ground contact time and CoM vertical motion, future studies should investigate changes in running economy with variations in T_C while maintaining similar ΔCoM_z.

Nonetheless, the results of the present study suggest that ΔCoM_z and T_C both significantly influence RE, with the combination of these two variables accounting for 58% of the variance in metabolic cost.

Prior research suggests that the amount of muscle used is a quantifiable predictor of metabolic cost in running (Kipp et al., 2018). A recent study reported that leg muscle activation accounts for 19.1% of the variability in running economy, but there was no relation between individual muscle activation and running economy (Tartaruga et al., 2012). We found that that there were increases in proximal muscle activation in the Biceps Femoris and Vastus Lateralis with deviations away from $\Delta CoM_{z,pref}$. The reason for these muscular changes remains unclear. This increase in MA of the larger and less efficient proximal muscles presumably contributed to the increase in metabolic cost seen with deviations away from $\Delta CoM_{z,pref}$. Additionally, we observed changes in the timing of the large proximal muscles as stride length and ΔCoM_z decreased. Both VL and BF activation increased in the earlier portions of in the gait cycle, and BF activation magnitude decreased during the late swing phase (70-90%). This is in agreement with Connick and Li (2014) who found that as stride length decreases (5-10%), muscle activation in the VL and BF began earlier in the gait cycle. In addition, Chumanov 2012, also found decreases in BF muscle activation during the swing phase as SL decreased. In the lower leg, Soleus activity was minimized at $\Delta CoM_{z,pref}$, and increased with changes from $\Delta CoM_{z,pref}$, whereas TA activation decreased as ΔCoM_z increased. At ΔCoM_z less than preferred, the increase in lower leg muscle activation was associated with increased SF and decreased SL. Prior research has observed similar changes in lower leg muscle activation and attributes these changes in MA with a change in landing posture (reduced foot-ground inclination angle) due to using an increased stride frequency (Heiderscheit, Chumanov, Michalski, Wille, & Ryan, 2011). Thus it likely that changes in leg muscle activation and thus running economy are the results of changes in gait kinematics associated with alteration in CoM vertical motion.

This experiment gives new insight into how changes in ΔCoM_z influence running economy, kinematics, and muscle activation. However, in this study, we only examined variations in ΔCoM_z at one speed and on a level treadmill. To gain a broader understanding of this complex relationship, future studies should examine how speed and incline slope (uphill and downhill) running influence preferred and optimal ΔCoM_z and its relation to running economy, biomechanics, and muscle activation. Nonetheless, results from the present study suggest that running economy is optimized at or near $\Delta CoM_{z,pref}$ (~6-8 cm) and that large changes from $\Delta CoM_{z,pref}$ negatively impact running economy. These results may be beneficial to running coaches and other researchers interested in maximizing and/or better understanding the determinants of running performance.

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APPENDIX A

HSU Biomechanics Lab

Medical History Questionnaire

Subject ID:________________ **Contact Phone or email: __________________________**

Age _______ Gender __________

Student ( ) Staff/Faculty ( ) Community ( ) Athlete ( )

YES NO In the past five years have you had:

☐ ☐ 1. Pain or discomfort in chest, neck, jaw, or arms

☐ ☐ 2. Shortness of breath or difficulty breathing at rest or with mild exertion

☐ ☐ 3. Dizziness or fainting

☐ ☐ 4. Ankle edema (swelling)

☐ ☐ 5. Heart palpitations (forceful or rapid beating of heart)

☐ ☐ 6. Pain, burning, or cramping in leg with walking

☐ ☐ 7. Heart murmur

☐ ☐ 8. Unusual fatigue with mild exertion

YES NO Currently….

☐ ☐ 9. Are you under the care of a physician?

☐ ☐ 10. Do you have an acute systemic infection, accompanied by a fever, body aches, or swollen lymph glands?

☐ ☐ 11. Do you have a neuromuscular or musculoskeletal disorder that is made worse by exercise?

☐ ☐ 12. Do you know of any reason why you should not do physical activity?

If you answered yes to any of these questions, please explain.

____
____
____
____
____

Other Health-Related Questions

YES NO

( ) ( ) 1. Have you had any surgery, serious illness, or serious injury in the last two years?

( ) ( ) 2. Are you pregnant?

( ) ( ) 3. Are allergic to isopropyl alcohol (rubbing alcohol)?

( ) ( ) 4. Do you have any allergies to medications, bees, foods, etc.?

( ) ( ) 5. Are you currently taking any medications, supplements, or pills? If so, please list on the next page.

( ) ( ) 6. Do you have any skin problems?

( ) ( ) 7. Do you have any other illness, disease, or medical condition (beyond those already covered in this questionnaire)?

( ) ( ) 8. Have you had any caffeine, food, or alcohol in the past 3 hours?

( ) ( ) 9. Have you exercised today?

( ) ( ) 10. Are you feeling well and healthy today?

If you answered yes to any of these questions, please explain.

____

____

____

____

Please list your current medications and/or supplements here. Include dosage and frequency.

Medication Dosage Frequency

____

____

____

Physical Activity and Running History

How long have you been running: ___________ years / months / weeks

What is your present longest run: ___________

What is your current 5k time: _________

What is your estimated amount of running in the last 2 weeks? _____ miles and/or ___ hours

I certify that the information I have provided is complete and accurate to the best of my knowledge.

Date ___________ Signature of Client

____

APPENDIX B

Pre-Experimental Instructions

For Vertical Motion Research Study

Please call 707-826-5973 if you have questions or can't make your appointment. You are scheduled to participate in a research study; your performance depends upon adherence to these instructions.

1. Do not perform heavy exercise in the 48 hours preceding your test.
2. Do not drink alcohol for 12 hours preceding your test.
3. Do not use caffeine (i.e. coffee) or nicotine (i.e. cigarettes) for 3 hours preceding your test.
4. Do not eat for 3 hours preceding your test.
5. Do not eat any food that may cause you discomfort the day of the test.
6. Avoid over-the-counter medications for the 12 hours preceding your test. However, cancel your appointment if you are ill and treat yourself accordingly. We can reschedule.

What to bring for research study:

1. Running shoes
2. Fitted shorts to run in
3. Spandex or other tight fitting shirt
4. Water bottle

Thank you for your cooperation!