ASYMMETRIC STEP FREQUENCIES INCREASE THE METABOLIC COST OF RUNNING

By: Eric N. Azua

Applied Biomechanics Lab

Department of Integrative Physiology

University of Colorado Boulder, CO

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Thesis Advisor: Dr. Alena Grabowski, Department of Integrative Physiology

Defense Committee: (Dr. Alena Grabowski) Department of Integrative Physiology, (Dr. David Sherwood) Department of Integrative Physiology, (Dr. Rebecca Ciancanelli) Student Academic Success Center

ABSTRACT

Purpose: Many individuals exhibit biomechanical asymmetries during running. Yet, despite the prevalence, it is unknown how these biomechanical asymmetries affect metabolic cost. Altering biomechanical variables such as peak and stance average vertical ground reaction force (GRF) production, contact time, stride frequency, leg stiffness, and peak horizontal GRF production, all influence muscular demands that can change the metabolic cost of running and affect distance-running performance. Therefore, we investigated how step frequency asymmetries affected these biomechanical variables and the metabolic cost of running.

Methods: 10 healthy runners ran on a force measuring treadmill at 2.8 m/s while matching their steps to an audible metronome that beat at different randomly selected asymmetric step frequencies (0, 7, 14, and 21%). We measured metabolic rates (i.e. net metabolic power), GRFs, and stride kinematics throughout each trial.

Results: For every 10% increase in step frequency and stance average vertical GRF asymmetry, net metabolic power increased 3.5% ($p<0.001$), and for every 10% increase in contact time asymmetry, net metabolic power increased 7.5% ($p=0.038$). Furthermore, for a 10% increase in peak braking and propulsive GRF asymmetry, net metabolic power increased 1.3 and 2.0%, respectively ($p<0.001$). Net metabolic power was independent of peak vertical ground reaction force ($p=0.422$), and leg stiffness ($p=0.054$) asymmetry.

Conclusion: Increases in step frequency, stance average vertical GRF, ground contact time, and peak braking and propulsive GRF asymmetries result in an increased metabolic cost of running. However, healthy runners manipulate these biomechanical variables differently and thus have variability in the metabolic demand of asymmetrical running.

Key Words: METABOLIC POWER, RUNNING ECONOMY, ASYMMETRIES

INTRODUCTION

Running is well represented by a spring-mass model, where the center of mass (COM) is portrayed by a point mass and the stance leg is represented by a massless linear spring (Fig. 1) (2, 11, 23, 24, 31). During the first half of the stance phase, the COM is lowered and decelerated as mechanical energy is stored through leg spring compression (5). The COM then reaches its lowest point at midstance when the leg spring is compressed. During the second half of stance, mechanical energy is returned as the leg spring extends and re-accelerates the body upward and forward (1, 2, 5). The elastic structures of the leg (i.e. tendons, ligaments, etc.) recycle a portion of the mechanical energy and influence overall leg spring mechanics, as a result, the mechanical input needed from the leg muscles is comparatively lower (1, 8, 21, 32). However, while the elastic structures reduce the muscular work required during running, the leg muscles still need to generate force for the elastic structures to operate, incurring a metabolic cost (1, 20, 27, 32, 32).

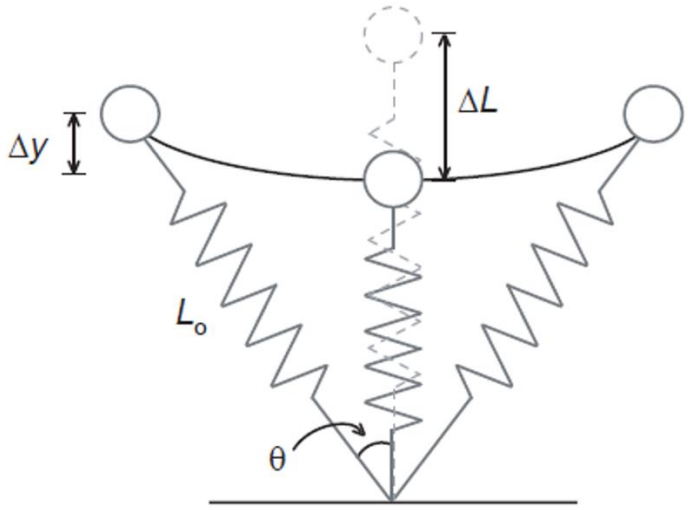

Figure 1. Running is represented by a simple spring-mass model (24). The model consists of a point mass representing the center of mass and a linear spring representing the leg. The leftmost position of this figure shows the model at the beginning of the stance phase, the middle position models the middle of the stance phase, where the leg spring is oriented vertically, and the rightmost position shows the end of the stance phase. The dashed leg spring displays the length of the leg spring without compression. L_o represents the leg spring at its initial length during the beginning of the stance phase. ΔL depicts maximum compression along the leg. Δy indicates the downward

vertical displacement of the center of mass, which is substantially smaller than ΔL. θ indicates half the angle swept by the leg spring during ground contact.

Metabolic cost is the amount of energy it takes to perform a given task over a given distance (1, 27), and is quantified by rates of oxygen consumption and carbon dioxide production. By reducing the metabolic cost of running, individuals can improve their distance running performance (16, 17). Active skeletal muscle is the primary consumer of metabolic energy during running (21, 32), therefore, an individual can alter their metabolic cost by adopting different running mechanics that change their muscular demands. Changes in running mechanics can be determined by measuring different biomechanical variables. The biomechanical variables that are most often associated with the metabolic cost of running are peak and stance average vertical force production (1, 13, 22, 27, 32), ground contact time (1, 21, 22, 27), stride frequency (1, 13, 31), leg stiffness (1, 11, 12, 26, 30, 31), and peak horizontal force production (1, 6), where modifications to each variable can influence muscular demand.

Averaged over a complete stride, a runner exerts a vertical force on the ground that is equal to body weight (W_b) regardless of running speed (1, 27). Muscle fibers consume metabolic energy to generate the force needed support body weight during ground contact (1, 7, 21, 22, 25, 27, 32). A longer ground contact time (t_c) enables runners to produce the required vertical force to support body weight with muscle fibers that contract slower, and consume less ATP due to fewer cross-bridges cycles (1, 3, 20). Therefore, decreasing average force production over a longer ground contact time could decrease the metabolic cost of running (1, 22). Kram and Taylor (22) derived an equation (Eq. 1) to model this behavior, where E_{Met} represents the net metabolic power in W,

W_b is body weight in N, and C denotes a cost coefficient, which remains near constant across different animals and running speeds (1, 22).

$$E_{Met} / W_b = C \cdot 1/ t_c \quad \text{Eq.1}$$

Previous studies have examined the effect of stride frequency on leg stiffness and show that when runners increase their stride frequency at a given running speed, the leg becomes more stiff (11). Leg stiffness (k_{leg}) is defined as the quotient of peak vertical ground reaction force divided by maximum leg spring compression (ΔL) (Eq. 2). Previous research has also found that increasing stride frequency compared to preferred increases the metabolic cost of running (15, 31). Therefore, increasing stride frequency and leg stiffness would increase the metabolic cost of running.

$$k_{leg} = F_{peak}/\Delta L \quad \text{Eq. 2}$$

Lastly, while peak horizontal GRFs are smaller in magnitude than peak vertical GRFs during level-ground running, peak braking and propulsive forces affect metabolic cost (1, 6). In fact, studies have shown that by applying an impeding horizontal force that was 6% of body weight, $\dot{V}O_2$ consumption increased by 30%, and by applying an aiding force horizontal force that was 6% of body weight, $\dot{V}O_2$ consumption was reduced by 15% (1, 6). Further, performing external work against an impeding load applied at the runner's waist increases the metabolic cost linearly with the magnitude of the load (34). Muscles produce braking and propulsive forces while running, thus, altering horizontal GRFs influences muscle force production, which leads to changes in metabolic cost.

Altogether, altering running biomechanics such as vertical force production, contact time, stride frequency, leg stiffness, and horizontal force production all influence muscular demand and the metabolic cost of running. Thus, we predict that increases in peak and average vertical force production, stride frequency, leg stiffness and peak horizontal force production will increase metabolic cost, while increases in contact time will decrease metabolic cost. However, it is not clear if the same metabolic trends persist if these biomechanical parameters were different between individual legs, causing a runner's gait to be asymmetric.

Many individuals exhibit biomechanical asymmetries during running. Biomechanical asymmetries are prevalent among people with abnormal gait (19, 29), asymmetric limbs (19), and those who have undergone a lower limb operation such as a leg amputation or hip, knee, or ankle surgery (13, 33). Yet, despite the prevalence of biomechanical asymmetries, it is unknown how these asymmetries affect running performance. For instance, Timoney et al. (33) reported that patients who received Anterior Cruciate Ligament reconstruction surgery display asymmetries in their walking mechanics a year after their operation. Such patients who return to running and competition after an injury may perform sub-optimally if asymmetries in their running mechanics increase their metabolic cost. Thus, asymmetric biomechanics between legs during running could impact an athletes' performance. Previous studies have examined asymmetries in biomechanical variables during running, however, no research has quantified the metabolic costs due to asymmetric running mechanics between legs of healthy runners. For example, Karamanidis et al. (18) found differences in ground contact time between legs that differed from 4.96% to 8.05% when healthy subjects were running at different running speeds. However, they did not record how

these biomechanical asymmetries affected metabolic cost. While no studies have quantified the metabolic costs of asymmetric running, previous studies have attributed an increased metabolic cost of walking to asymmetric biomechanics in healthy individuals. Ellis et al. (10) found that increasing step time asymmetry by 23% increased the metabolic cost of walking by 17% compared to a walker's preferred, symmetric gait. However, running and walking are biomechanically different, thus, we sought to address whether imposed stride kinematic asymmetries increase the metabolic cost of running for young healthy runners. We hypothesized that the metabolic cost of running would increase with an increase in step frequency ($Freq_{step}$), ground contact time, peak and stance average vertical GRFs, peak braking and propulsive GRFs, and leg stiffness asymmetries.

METHODS

Participants

Ten healthy runners (Table 1, 6 M, 4 F) volunteered. Each participant ran at least three days a week, and could run 5km under 30 minutes. Prior to participation, each runner provided informed written consent according to the University of Colorado Boulder Institutional Review Board.

Table 1. Participant Characteristics (Mean ± S.D.)

Participants (n)	10
Leg Length (m)	0.90 ± 0.03
Preferred Step Frequency (Hz)	1.35 ± 0.07
Age (yrs)	22.9 ± 6.2
Height (cm)	171.6 ± 5.0
Body Mass (kg)	65.5 ± 4.9

Protocol

Participants completed two identical testing sessions in the Applied Biomechanics Lab that were separated by at least 24 hours.

During the first session, participants performed a six-minute standing trial, as well as a series of seven different running trials on a 3D force measuring treadmill (Treadmetrix, Park City, Utah). The first running trial required participants to run for 12 minutes at 2.8 m/s while we measured GRFs from 10 consecutive strides (20 steps) during the last minute of the trial. Subsequently, we calculated the runner's preferred step frequency ($Freq_{step}$), the inverse of ground contact time (t_c) plus aerial time (t_a) (Eq. 3), using a custom Matlab script (Mathworks Inc., Natick, MA, USA).

$$Freq_{step} = 1/ (t_c / t_a) \quad \text{Eq. 3}$$

For the second running trial, subjects ran for 6 minutes at 2.8 m/s to the beat of a custom metronome set to audibly "tick" at their preferred symmetric step frequency, calculated from the initial running trial. During the third trial, participants ran to the beat of the metronome that elicited an asymmetric step frequency while maintaining preferred stride frequency (Fig. 2) This trial was set at the highest step frequency asymmetry used in the study, which was 21%.

We used the symmetry index (SI) equation (Eq. 4) to calculate the predetermined beat of the metronome based on each participant's preferred step frequency, in addition to the exhibited step frequency asymmetry from each trial. A 21% change in step frequency indicates that within one stride, there was a 21% increased step frequency in one leg compared to the average step frequency (preferred step frequency), and a 21% decreased step frequency in the other leg compared to the

average step frequency (preferred step frequency). Stride frequency remained constant across all trials. A numerically greater SI is representative of greater asymmetry, and perfect symmetry is denoted by a SI of 0%. Individual asymmetries were calculated using the absolute value of the symmetry index and were expressed as a percentage (10, 14, 28) (Eq. 4).

$$SI = \left| \frac{StepFreq(leg1) - StepFreq(leg2)}{0.5 \text{ x } (StepFreq(leg1) + StepFreq(leg2))} \right| x\ 100\% \quad \text{Eq. 4}$$

After participants were habituated running to the metronome at the least (0% asymmetry) and most (21% asymmetry) asymmetric running trials, they ran four more trials to beat of the metronome at different randomly selected asymmetric step frequencies. For each trial, we imposed an asymmetrical step frequency derived from the corresponding participant's preferred (symmetric) step frequency using the SI that matched a 0, 7, 14, or 21% change from average step frequency (10, 14, 28) (Fig. 2). Every individual's preferred step frequency was used as the baseline (0% asymmetric) for the following asymmetric trials. Each trial was preceded with 5 minutes of rest, was performed at 2.8 m/s, and lasted for 6 minutes, apart from the initial 12-minute running trial. Levels of asymmetries were selected based on the feasibility of attainment during pilot testing. We measured actual step frequencies by using each subject's GRFs, and their actual asymmetries by using their measured step frequencies and the SI equation.

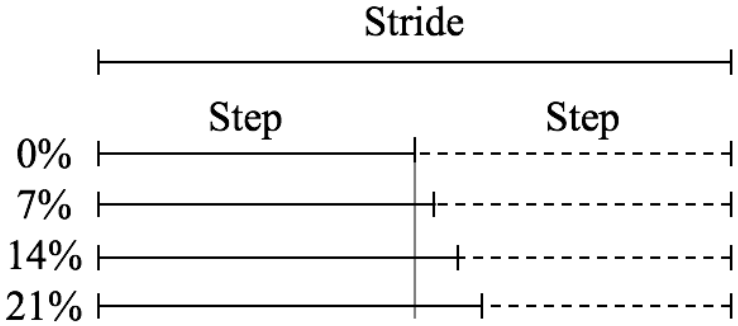

Figure 2. Footfall patterns for step frequencies asymmetries of 0, 7, 14, and 21%. 0% refers to preferred step frequency. While step frequency differed between legs, there was no change in overall preferred stride frequency.

During the second session, participants completed the same protocol as that of the first session, however, the order of the last four asymmetric running trials were re-randomized. Subjects completed two sessions to establish if there was any day-to-day variability.

Data Collection

We measured the vertical and anterior-posterior components of the GRFs for 30 seconds after minutes 3 and 5 of each running trial. We collected GRFs at 1000 Hz, filtered them using a 4^{th} order low-pass Butterworth filter with a 30 Hz cutoff, and then used the filtered data to calculate GRF parameters in the horizontal and vertical directions, stride kinematics (step frequency and ground contact time), and leg stiffness for both legs using the spring mass model (2, 11, 13, 24, 31) from 10 consecutive strides with a custom MATLAB script. We set our GRF threshold at 10 N to detect periods of ground contact.

Metabolic Cost

Both sessions were at the same time of day and subjects fasted for at least three hours prior to experimental trials to decrease any potential day-to-day variability in metabolic rates. We measured rates of oxygen consumption and carbon dioxide production using indirect calorimetry (ParvoMedics TrueOne 2400, Sandy, UT) and averaged these rates over the last two minutes of each trial. We then used average metabolic rates to calculate metabolic power using a standard equation (4). We subtracted standing metabolic power from the respective participant's metabolic power from the same day's running trials, then we divided by user mass (including running clothing), to yield normalized net metabolic power. Respiratory exchange ratios (RER) were constantly monitored to ensure that participants consumed primarily aerobic metabolism (RER<1.0).

Statistical Analysis

We performed independent linear mixed model analyses to test the influence of step frequency, peak and average vertical GRF, ground contact time, leg stiffness, and peak braking and propulsive GRF asymmetries on the percentage change in net metabolic power (from the symmetric metronome running trial) for each participant. We then used linear mixed model analyses to test the interactions that ground contact time and stance average vertical GRF of the subject's "fast" leg (the leg with a shorter step time) had on net metabolic power, as well as the interaction that ground contact time had on stance average vertical GRF. For each statistical test, we controlled for session and tested each session/biomechanical variable interaction. We set significance as p=0.05 and performed statistical analyses using R-studio (V1.0.136, Boston, MA, USA).

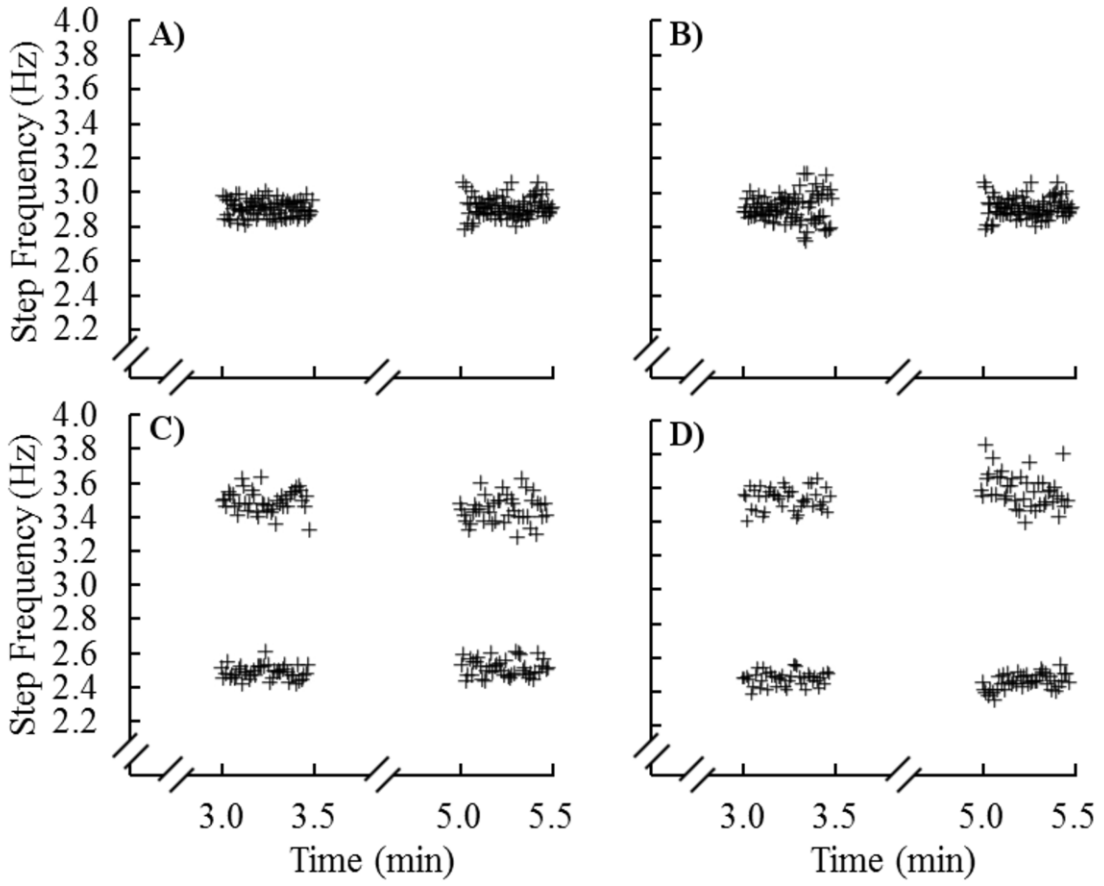

Figure 3. Step frequency (Hz) for one subject at 3 and 5 minutes, which were mid-trial and end trial, respectively, at four different asymmetries, A) 0%, B) 7%, C) 14%, and D) 21%. Each plus sign represents a single step that was taken during each 30-second interval. Conditions A and B were trials where runners achieved a step frequency asymmetry steady-state. We defined this as a drift in step frequency asymmetry, between 3 and 5 minutes, that was less than two standard deviations from the mean exhibited in the symmetric running trials (2.08%). **A)** Metronome = 0%, Actual = 3.97% and 2.41% at 3 and 5 minutes, respectively. **B)** Metronome = 7%, Actual = 3.49% and 2.95% at 3 and 5 minutes, respectively. **C)** Metronome = 14%, Actual = 34.27% and 30.34% at 3 and 5 minutes, respectively. **D)** Metronome = 21%, Actual = 35.42% and 41.46% at 3 and 5 minutes, respectively.

RESULTS

For the symmetric metronome running trials, we utilized the difference in step frequency asymmetry between minutes 3.0 and 5.0, which was 0.82 ± 0.63% (average ± standard deviation), to determine steady-state running. Based on the assumption that runners achieve biomechanical

steady-state when running to an audible symmetric beat (11, 31), the only asymmetric experimental running trials (0, 7, 14, & 21% asymmetry) that were analyzed were the ones where runners achieved a step frequency asymmetry steady-state. We defined this as a drift in step frequency asymmetry, between minutes 3 and 5, that was less than two standard deviations from the mean exhibited in the symmetric running trials (2.08%) (Fig. 3). Overall, 41 asymmetric running trials between both sessions achieved biomechanical steady-state.

Running session did not affect the metabolic cost of running, nor did it interact with any biomechanical variables regarding metabolic cost ($p \geq 0.05$), thus it was removed from our statistical analyses. For every 10% increase in step frequency and stance average vertical GRF asymmetry, net metabolic power increased 3.5% ($p<0.001$) (Fig. 4). For every 10% increase in contact time asymmetry, net metabolic power increased 7.5% ($p=0.038$). Furthermore, for a 10% increase in peak braking or propulsive GRF asymmetry, net metabolic power increased 1.3 and 2.0%, respectively ($p<0.001$). Net metabolic power was independent of peak vertical ground reaction force ($p=0.422$), and leg stiffness ($p=0.054$) asymmetry.

For every 1 unit increase in body weight (BW), fast leg average vertical GRF decreased net metabolic power by 17.8% ($p<0.001$), and for every 1 sec increase in the fast leg's ground contact time, fast leg average vertical GRF decreased by 4.53*BW ($p<0.001$). Net metabolic power was independent of fast leg ground contact time ($p=0.452$).

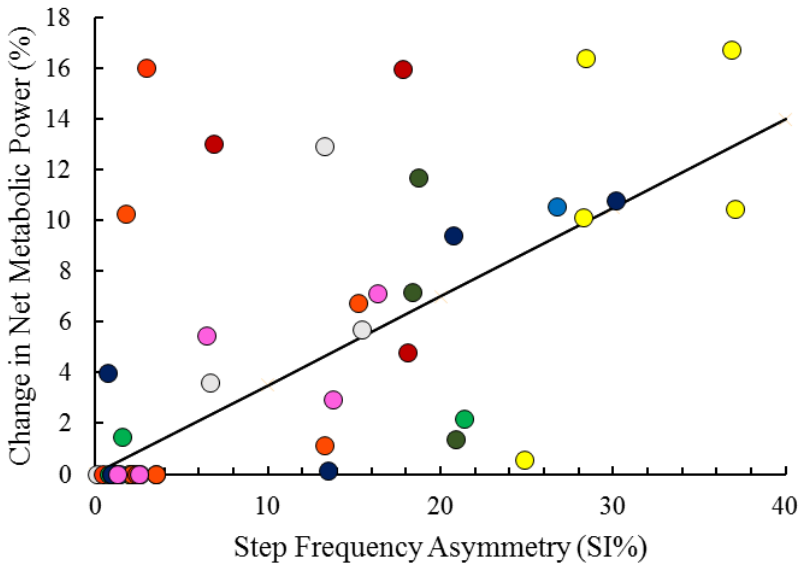

Figure 4. Change in net metabolic power (NMP) due to an implemented step frequency asymmetry in 10 runners during each experimental running trial. Each color represents a different individual. Change in NMP (%) = 3.5 x step frequency asymmetry (%) + 0.006. R^2= 0.361

DISCUSSION

The goal of this study was to examine the effects of implemented step frequency asymmetries on the metabolic cost of running in healthy runners. We found that net metabolic power increased by 3.5% for every 10% increase in step frequency asymmetry ($p<0.05$). Thus, on average, subjects running at a 21% step frequency asymmetry required 7.35% more net metabolic power compared to their preferred step frequency. While our data indicates that metabolic cost increases with the level of asymmetry, it also demonstrates that increases in metabolic cost due to the implemented step frequency asymmetry were varied across subjects. While some subjects had large changes in net metabolic power at low step frequency asymmetries, others had the opposite outcome (Fig. 4). The correlation between the percent change in step frequency asymmetry and the percent change in net metabolic power was moderate (R= 0.601). For example, a 7% step frequency asymmetry did not influence every subject's change in net metabolic power equally. At a 7% asymmetry, some runners had a 7% change in net metabolic power, while others had a 14%

change. These results may indicate that individual runners changed their running biomechanics differently at high and low asymmetries. Nonetheless, in general, asymmetric step frequencies increase metabolic power while running.

Our results are comparable to the results of Ellis et al. (10), who varied walking step time asymmetries in healthy humans. Their results indicate that a 23% increase in step time asymmetry required a 17% increase in metabolic power, and a 42% step time asymmetry required 31% more metabolic power than symmetric walking. This linear increase in metabolic power allows us to assume that a 10% increase in step time asymmetry during walking increases metabolic power by 7.4%, which is over twice the percentage increase in metabolic power that we observed for running. These finding lead us to believe that step frequency asymmetry has a stronger effect on metabolic power during walking compared to running. This could be due to the differences in energy transfer in walking and running. Walking uses the exchange of kinetic and gravitational potential energy during single support to minimize the amount of muscular force (10), but also exacts a muscular cost for the work performed during the step-to-step transition (9). Running utilizes elastic energy storage and return provided by the tendons, ligaments, muscles, etc. Walkers on average tended to increase the amount of ground contact time on their "faster" leg; whereas in running, an increase in ground contact time would allow muscle fibers to contract with greater force. However, since energy is not primarily translated through elastic elements in the leg to propel the COM upward in walking, walkers may have to recruit an even greater muscle volume to transition into the next step, thus demanding a greater metabolic cost with changes in step frequency asymmetries.

Asymmetries in both ground contact time and stance average vertical GRF required greater net metabolic power. Asymmetric step frequencies are achieved by modifying either contact time and/or aerial time between the legs. In our study, there was not one consistent way that individual runners chose to manipulate step frequency. Individual runners modified contact time and/or aerial time between legs to match the implemented step frequency asymmetry; however, ground contact time has a greater influence on total metabolic cost than aerial time. Studies have shown that leg swing, requires ~7% of the net metabolic power for running, while body weight support and forward propulsion constitute ~80% of the net metabolic power. While decreases in aerial time do require a greater muscular input to swing the leg forward at a faster velocity, the recruitment of muscle fibers needed to generate enough inertia to overcome air resistance are minimal in comparison to the recruitment of muscle fibers to generate force to support body weight. Surprisingly, we found that shorter ground contact times did not result in an increase of net metabolic power ($p=0.452$), however, shorter ground contact times did increase average vertical force production ($p<0.001$). This data implies that runners typically used more vertical force to push off from the leg that had a shorter step time, but does not explain the increase in net metabolic power because a 1 unit increase in body weight in fast leg stance average vertical GRF resulted in a 17.8% decrease in net metabolic power ($p<0.001$). The overall decrease in net metabolic power due to increased stance average vertical GRFs could potentially be due to the asymmetrical vertical force production between legs.

The cost of generating braking GRFs is metabolically cheaper than generating propulsive GRFs during level-ground running (1, 6). This finding could explain why a 10% increase in peak braking and propulsive GRF asymmetry resulted in a 1.3% and 2.0% increase in net metabolic power,

respectively. While there is little evidence that shows how asymmetries in peak propulsive forces affect metabolic cost, we speculate that changes in asymmetric peak propulsive and braking GRFs could require increased muscular demand from one leg to maintain a constant velocity since the legs are moving at different step frequencies (2).

Neither changes in peak vertical GRF nor leg stiffness asymmetries influenced changes in net metabolic power ($p>0.05$). Changes in leg stiffness require runners to adjust the rate and amount of force generated by the leg muscles, thus, altering metabolic cost (12). However, previous research on runners with unilateral transtibial amputations found that varying prosthetic stiffness, thus, varying peak vertical GRFs and leg stiffness between legs, did not affect the metabolic cost of running (13). These results between athletes with and without unilateral leg amputations require further investigation of if, and how, leg stiffness and GRF asymmetries influence metabolic cost.

One potential limitation of our study was each runner's inability to accurately match the beat of the metronome. Runners were instructed to initiate contact with the treadmill every time the metronome made an audible "tick", yet this proved difficult. This could have been a result of runners losing focus of their steps while carefully listening to the audible metronome, or potentially being unbalanced while running asymmetrically. Even when runners seemed to visibly match the metronome, their actual step frequency asymmetry deviated from the desired step frequency asymmetry. The largest deviation from the desired experimental step frequency asymmetry was 20%. While one runner was attempting to run to a 21% asymmetric step frequency, their actual step frequency asymmetry was 41%. However, we used the change in each subject's actual step frequency asymmetry in our analyses. Secondly, the mechanism we used to explain changes in

metabolic cost is the recruitment of either a greater volume or more economical muscle fibers, however, we did not measure changes in muscle activity or muscle recruitment in this study. Thus, changes in muscular demands present in asymmetric running are based on speculation. Therefore, along with measuring metabolic demand, future studies should use electromyography to determine changes in leg muscle activity while subjects run at asymmetric step frequencies.

We measured the effects of asymmetric step frequencies in healthy, non-amputee runners. However, due to the asymmetric biomechanics already present in people with an amputation using running-specific prostheses (13), future studies should investigate how implemented step frequency asymmetries affect the metabolic cost of running in athletes with a leg amputation. Grabowski et al. (13) found that stance average vertical GRF was approximately 9% less for the affected leg compared with the unaffected leg of athletes with a unilateral transtibial amputation across a range of speeds from 3 m/s up to top speed. Based on our results, a 9% asymmetry in stance average vertical GRF suggests that the metabolic cost of running could increase by 3.15% due to asymmetric biomechanics alone. Thus, future studies are needed to understand how biomechanical asymmetries influence the metabolic cost of runners with an amputation.

Overall, our data supports our hypothesis that increased step frequency, ground contact time, stance average vertical GRF, and peak braking and propulsive GRF asymmetries result in an increased metabolic cost of running. However, our hypothesis that changes in peak vertical GRF and leg stiffness asymmetries would increase metabolic cost was not supported. While our data suggests that changing biomechanical variables between the legs of healthy runners can influence their metabolic cost, there was a lot of individual variability. Overall, people with symmetric

biomechanics should be able to lower their metabolic cost while running, and we speculate that this may lead to better running performance.

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