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International Journal of EXERCISE SCIENCE

Original Research

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ABSTRACT

International Journal of Exercise Science 13(4): 427-437, 2020. Running economy (RE) is defined as the oxygen consumption (VO_2) or caloric unit cost required to move at a specific velocity and is an important performance marker. Ground contact time (GCT) has been associated with RE; however, it has not been established how GCT imbalances between feet impact RE. Purpose: Determine the relationship between cadence, GCT, and GCT imbalances and RE. Methods: 11 NCAA Division I distance runners (7 male) completed a graded exercise test on a treadmill to determine lactate threshold (LT) and VO_2max. Body composition was also assessed via DEXA. Subjects ran with a heart rate monitor capable of measuring cadence, GCT, and GCT balance between feet. VO_2 and respiratory exchange ratio were recorded over the last minute of the 5-minute stages. RE expressed as caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$) was calculated for the stage determined to be just below the LT (prior to > 4mmol/L) and was correlated with cadence, GCT, and GCT imbalance by Pearson correlations. Results: Pearson correlations between RE and the running dynamics measures were as follows: cadence (r = -.444, p = .171), GCT (r = .492, p = .125), GCT Imbalance (r = .808, p < .005). An independent t-test revealed greater (p = .023) leg lean mass imbalances in runners with larger GCT imbalances compared to runners with smaller GCT imbalances. Conclusion: GCT imbalances are strongly related to impaired RE. Future research should determine how to improve GCT imbalances and if doing so improves RE.

KEY WORDS: Distance running, biomechanics, endurance performance, track

INTRODUCTION

In addition to a runner's maximal oxygen consumption (VO_2max) and lactate threshold (LT), running economy (RE) is considered a key endurance performance determinant (9). Previous reviews on RE (2) offer a variety of ways RE can be measured and expressed. RE can be expressed as oxygen consumption (VO_2) relative to body mass per minute ($ml\ O_2 \cdot kg^{-1} \cdot min^{-1}$) at a given speed or as the oxygen cost relative to body mass and distance covered ($ml\ O_2 \cdot kg^{-1} \cdot km^{-1}$) in order to normalize for differing speeds. Additionally, since VO_2 alone does not take into account substrate utilization, RE can also be expressed as the caloric unit cost ($kcal \cdot kg^{-1} \cdot km^{-1}$) (2). Improved RE, as indicated by a lower VO_2 or caloric unit cost, are advantageous as it represents the ability to work at a lower relative percentage of VO_2max at a given work rate, and also reduces the rate of energy depletion.

RE has been linked to several running dynamics measures, such as cadence, stride length, vertical oscillation (VO), and ground contact time (GCT). Previously, most of these markers would have to be measured in a laboratory setting. However, recent advances in wearable technology allow for consumers to track many of these metrics through the use of devices that incorporate accelerometers into heart rate monitors or separate wearable pods. Of these key running dynamic markers, it has been shown that too long of a stride length, and correspondingly slow cadence, result in impaired RE (6). There seems to be a u-shaped relationship between RE and cadence, with experienced runners naturally selecting slightly slower to near optimal cadences, and more novice runners self-selecting slower than optimal cadences (4, 6, 11).

The VO ratio is described as the ratio of vertical displacement to stride length and is another running dynamic measure that can be tracked with these new devices. In addition to slower cadences, excessive vertical oscillation for a given running speed has been associated with impaired RE (2). Likewise, steeper stride angles have also been shown to be negatively correlated with RE (18).

Ground contact time can be defined as the average time each foot spends in contact with the ground while running. Shorter GCT has been shown to be associated with improved RE in European runners compared to North African runners (17). Though some studies have shown decreased GCT to be associated with improved RE (12, 15), a review of studies comparing the relationship between GCT and RE yield equivocal findings (11). It has been suggested that decreased GCT may be linked to improved RE due to concurrent increases in leg stiffness, independent of cadence (12). GCT is typically reported as the average GCT per foot strike for both feet. GCT balance can be described as the percentage of time spent on one foot compared to the other. This is an additional marker that can be tracked by new wearable devices. There is a lack of research regarding the effect of such imbalances or asymmetries on RE. While one study has shown that artificially induced step time asymmetries impair RE (3), to our knowledge, there are no studies that have looked at the effects of differences in GCT between feet.

Therefore, the purpose of this study was to determine the relationship between GCT imbalances, GCT, cadence, and VO ratio on RE in National Collegiate Athletic Association (NCAA) Division I distance runners.

METHODS

Participants

Distance runners were recruited from an NCAA Division I athletic program. A total of 11 subjects (male: n = 7, 21 ± 1 years; female: n = 4, 19 ± 1 years) completed the study. All of the runners specialized in 1500m to 10,000m, with the exception of one 800m specialist. All subjects were healthy, injury-free, and reported no signs or symptoms of cardiovascular disease. Testing occurred 1-week following the end of the spring competition season and the conclusion of the outdoor track and field conference championships. Subjects were asked to abstain from caffeine and supplements on the day of testing. This research was carried out fully in accordance to the ethical standards of the International Journal of Exercise Science (14). All subjects provided written informed consent prior to the start of testing and all procedures were approved by the institutional review board. Sample size estimates (G*Power 3.1.9.2) revealed that for a coefficient of determination of 0.64, 9 subjects would be needed to achieve power of 0.8 with an α of 0.05.

Protocol

Graded Exercise Test: Subjects completed a graded exercise test (GXT) on a motorized treadmill (Woodway, Waukesha, WI) to determine LT and VO_2max. During testing, subjects wore a heart rate monitor (HRM-Tri/920XT, Garmin, Olathe, KS) capable of measuring cadence, GCT, GCT balance between left and right feet, and the vertical oscillation (VO) ratio. Running dynamic measures from the Garmin heart rate strap were previously validated with a motion capture system (ICC: Cadence, .931; VO, .963; GCT, .749) (1). VO_2 and the respiratory exchange ratio (RER) were monitored continuously throughout the testing (TrueOne 2400, Parvo Medics, Sandy, UT).

The GXT protocol was established based on the individual runner's predicted 10k pace, as previously described by Daniels (5). To determine the LT, the protocol consisted of 3-5, 5-minute stages of increasing speeds (134 meters $\cdot min^{-1}$; 0.5 miles $\cdot hour^{-1}$; .8 kilometers $\cdot hour^{-1}$) at 0% grade with 2 minutes rest between stages. The protocol was designed to reach the predicted 10k pace at the fourth stage. Blood lactate was measured from capillary blood samples (fingertip) at the conclusion of each stage while the subject straddled the treadmill belt. Blood lactate samples were analyzed using a portable lactate analyzer (Lactate Plus, Nova Biomedical, Waltham, MA). Once a participant's blood lactate exceeded the LT of 4 mmol/L, the LT portion of the test was ended. Following 5 minutes of rest, subjects then completed the VO_2max portion of the test. Subjects ran at the same speed determined from the final stage of the LT protocol, but 1% grade was added each minute until volitional exhaustion. VO_2max was determined from the highest average VO_2 recording over 1 minute.

Running Economy and Running Dynamics: In this study RE was assessed by determining the caloric unit cost (kcal $\cdot kg^{-1} \cdot km^{-1}$). Caloric unit cost was determined for each runner for the stage prior to reaching the > 4 mmol/L measure. The average VO_2 and RER for the final minute of this 5-minute stage was used to calculate the caloric unit cost using non-protein based RER tables. The average cadence, GCT, GCT balance, and VO ratio was calculated for the same stage.

To make these running dynamics calculations, the Garmin device collected data continuously throughout the GXT. The Garmin's data recording settings were set to "every second" recording. Following the GXT, the Garmin FIT file was uploaded to a separate software program (Golden Cheetah, v3.4) to access the raw data. This was done to isolate the data from the 5 minute stage of interest and to capture only steady state running speed/mechanics. Essentially, this allowed for the calculation of the averages for each dependent variable across the 5-minute stage, similarly to if the device had simply recorded a session or split for that segment alone.

The data utilized did not include any periods of acceleration or deceleration of the treadmill from the beginning or end of the stage.

GCT imbalances were calculated as the absolute difference in the percentage of time spent on the left vs. right foot during ground contact. For example, if the device depicted a GCT balance of 51% left foot, the GCT imbalance was calculated as 2% (51% left – 49% right). VO ratio was calculated as vertical oscillation (cm) divided by stride length (m).

Body Composition Assessment: Approximately 20-30 minutes following all GXT procedures, body composition was assessed via dual-energy x-ray absorptiometry (DEXA GE Prodigy, Chicago, IL). Body composition scans were analyzed to determine differences in lean mass between the left and right trunk, legs, and total body using manufacture recommended anatomical locations to set the regions of interest. Thigh lean mass differences between legs was determined by custom set regions of interest, as previously described (20). Likewise, femoral length and total leg length was determined by custom set regions of interest set at the proximal end of the greater trochanter to the middle of the knee joint and to the distal end of the medial malleolus, respectively.

Statistical Analysis
RE was correlated with cadence, GCT, GCT imbalance, and VO ratio by Pearson correlations. GCT imbalances were also correlated to the muscle mass and bone length metrics from the DEXA scan. Additionally, an independent sample t-test was used to compare the DEXA metrics between the runners with the greatest GCT imbalances to the runners with the least GCT imbalances. Analyses were made using the Statistical Package for the Social Sciences (SPSS 25, IBM Corporation, Armonk, NY). An α-level of .05 was use for determination of significance for all statistical tests.

RESULTS

VO_2max and LT results from the GXT, as well as body fat percentage data from DEXA, are displayed in Table 1.

Table 1. GXT and body composition data (mean ± SD) from NCAA Division I distance runners.

	VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$)	LT (% VO_2max)	Body Fat (% Fat)	Sample Size (*n*)
Men	68.6 ± 4.9	80 ± 8	15.8 ± 3.4	7
Women	59.3 ± 1.1	83 ± 5	22.1 ± 5.2	4

All RE data are expressed as the caloric unit cost of running ($kcal \cdot kg^{-1} \cdot km^{-1}$) with a lower caloric unit cost indicating better RE. Scatterplots illustrating the relationship between RE expressed as caloric unit cost and the measured running dynamic variables are displayed in Figure 1, and the corresponding Pearson correlations are displayed in Table 2. There was a strong positive relationship between GCT imbalances and caloric unit cost (Table 2). Larger GCT imbalances were associated with an increased caloric unit cost, with over 65% of the variance being explained by GCT imbalances (R^2 = .65, 95% CI: .37 to .93) (Figure 1A). Caloric unit costs were 0.0354 kcal ·kg^{-1} ·km^{-1} greater for every 1% increase in GCT imbalance, representing an ~3.7% increase in metabolic cost for each 1% increase in imbalance.

The Pearson correlations between caloric unit cost and the other running dynamics measures (cadence, GCT, and VO ratio) as well as the speed the athletes were tested are also displayed in Table 2, none of which were significant. Raw data showing all measured variables for each individual subject ranked from the most to least economical runner in terms of caloric unit cost of running are displayed in Table 3.

There were no significant correlations between GCT imbalances and muscle mass and leg length imbalances measured by DEXA, as displayed in Table 4. An independent sample t-test comparing the 6 runners with the smallest GCT imbalances to the 5 runners with the largest GCT imbalances revealed significantly greater (t (9) = 2.73, p = .023; d = 1.56) leg lean mass imbalances in the runners with larger GCT imbalances (.44 ± .35 kg) compared to the runners with smaller GCT imbalances (.05 ± .05 kg). No significant relationships were found between trunk or total lean mass imbalances or leg length imbalances and GCT imbalances (Table 4).

Table 2. Relationship between running dynamic variables and running economy expressed as the caloric unit cost of running.

		GCT Imbalance	GCT	Cadence	VO Ratio	Speed
Caloric Unit Cost	Pearson Corr. (r)	.808**	.492	-.444	.335	.176
kcal ·kg^{-1} ·km^{-1}	Sig. (2-tailed)	.003	.125	.171	.315	.605

GCT: Ground Contact Time; VO: Vertical Oscillation; **p < 0.005; (n = 11)

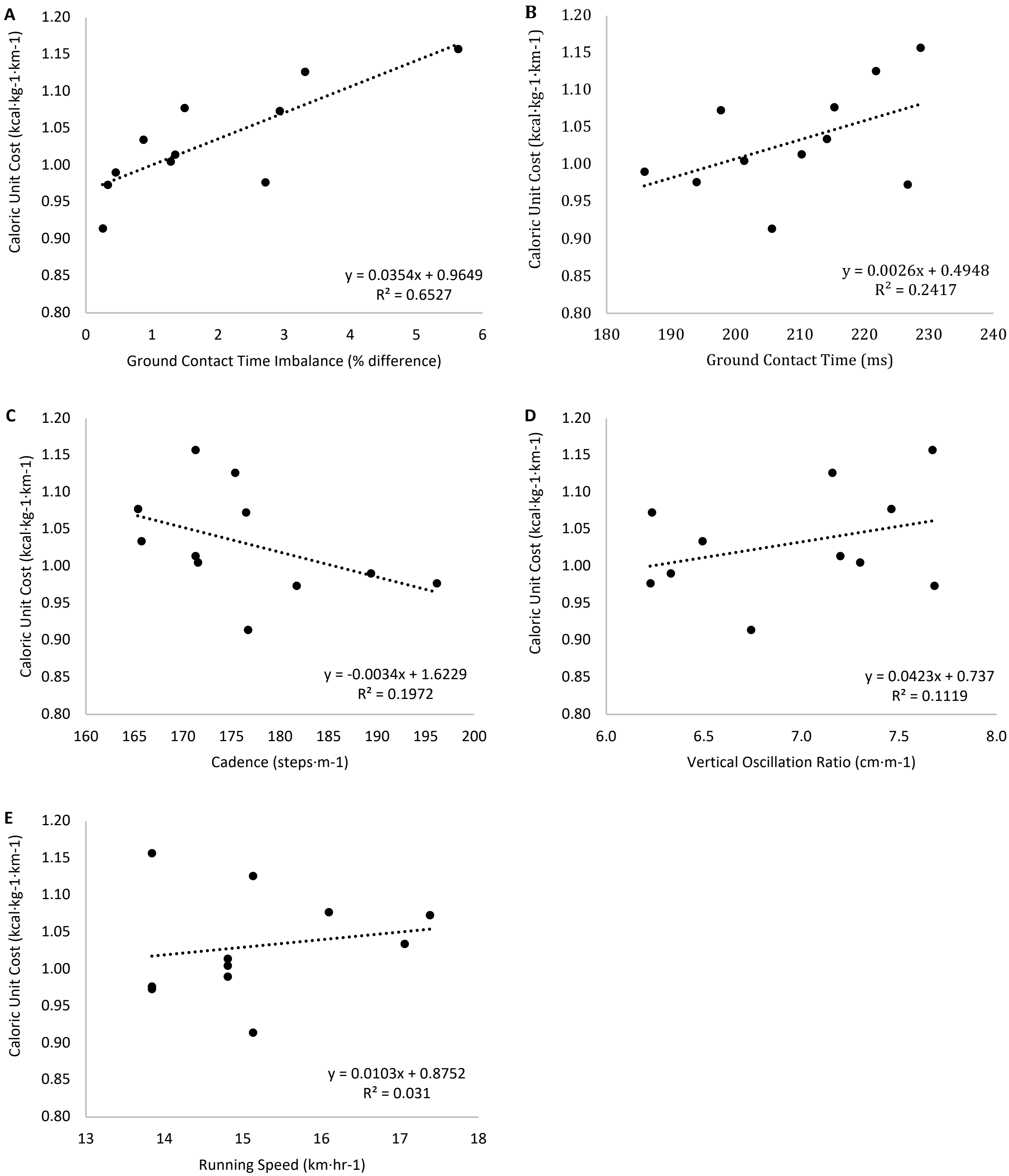

Figure 1. Relationship between running economy expressed as the caloric unit cost of running and ground contact time imbalances (A), ground contact time (B), cadence (C), vertical oscillation ratio (D), and tested running speed (E) in NCAA Division I distance runners (n = 11).

Table 3. Raw data for individual subjects ranked from least to greatest caloric unit cost of running.

Subject	Mass	Speed	VO_2	Economy	Caloric Unit Cost	GCT	Cadence	Imbalance	VO Ratio
1	55.5	15.13	46.7	185.2	0.914	206	177	0.25	6.74
2 ♀	56.4	13.84	45.5	197.2	0.974	227	182	0.33	7.68
3 ♀	47.3	13.84	45.2	195.9	0.977	194	196	2.71	6.22
4 ♀	56.4	14.81	48.9	198.2	0.990	186	189	0.45	6.33
5	57.3	14.81	50.0	202.6	1.005	201	172	1.28	7.30
6	70.9	14.81	50.2	203.4	1.014	210	171	1.35	7.20
7	72.7	17.06	58.7	206.5	1.034	214	166	0.87	6.49
8	68.6	17.38	63.3	218.5	1.073	198	176	2.93	6.23
9	63.6	16.09	59.0	220.0	1.078	215	165	1.49	7.46
10	65.9	15.13	57.1	226.5	1.126	222	175	3.31	7.16
11 ♀	59.5	13.84	53.8	233.2	1.157	229	171	5.63	7.67

♀ = female subject.
Units: Mass, kg. Speed, $km \cdot hr^{-1}$. VO_2, $ml \cdot kg^{-1} \cdot min^{-1}$. Economy, $ml \cdot kg^{-1} \cdot km^{-1}$. Caloric unit cost, $kcal \cdot kg^{-1} \cdot km^{-1}$. GCT, ms. Cadence, $steps \cdot min^{-1}$. Imbalance, GCT % difference. VO Ratio, vertical oscillation (cm) $\cdot$ stride length $(m)^{-1}$

Table 4. Relationship between GCT imbalances and DEXA muscle and bone imbalances.

		Thigh Lean Imb.	Leg Lean Imb.	Trunk Lean Imb.	Total Lean Imb.	Femur Length Imb.	Leg Length Imb.
GCT Imb. (%)	Pearson Corr. (r)	-.293	.350	-.052	.238	.106	.150
	Sig. (2-tailed)	.490	.292	.879	.481	.755	.660

GCT: Ground Contact Time; Imb: Imbalances between legs; (n = 11).

DISCUSSION

While the impact of GCT and RE has been of interest for some time (16), this is the first study to the authors' knowledge to look at the relationship between GCT imbalances and RE. The present data demonstrate a strong relationship between GCT imbalances and impaired RE. The current data show an ~3.7% increase in metabolic cost for every 1% increase in GCT imbalance observed across runners. This parallels previous research that showed for every 10% increase in forced step time asymmetry, there was a 7.8% increase in oxygen cost (3). Interestingly, the force step time asymmetries elicited in the previous study did not result in actual differences in contact times (3). It should also be noted that while asymmetries were artificially created in the previous study, the imbalances observed in the present study were naturally occurring in a population of injury free NCAA Division I runners.

While we are aware the observed correlations between GCT imbalance and RE were determined across a sample of different runners, and we cannot declaratively state that such changes in GCT imbalance elicited in an individual would cause equivalent changes in RE, we feel it is important to provide some practical context to the observed relationship. If we were to extrapolate these findings, for a 70 kg runner in a marathon, this would equate to 105 kcal of increased energy expenditure in the race for each 1% imbalance in GCT. Thus, as an example, a runner with a 3% GCT imbalance (51.5% GCT right, 48.5% GCT left) would expend ~315 additional kcal for the marathon. When expressed in terms of oxygen cost, the increases observed with greater GCT imbalances equate to > 1 metabolic equivalent, precisely 3.9 ml $\cdot kg^{-1} \cdot min^{-1}$, for every 2% increase in GCT imbalance for a 70 kg runner running at 15 km $\cdot hr^{-1}$. For a runner with a VO_2max of 60 ml $\cdot kg^{-1} \cdot min^{-1}$, this would represent working at an almost 7% greater fraction of their maximal aerobic capacity. This increased rate of energy depletion and reduced economy would be expected to impair performance.

In the present study, there were only weak to moderate (non-significant) correlations between RE and GCT and cadence. The strength of the relationship observed presently between GCT and RE, although not significant, was similar to previous research relating GCT to RE (r = .49) (15). A limitation to interpreting GCT and cadence in the present study is that the speed at which RE was calculated was not the same for every runner. Because the GXT was a customized protocol, RE was instead measured at the speed/stage just prior to each runner's LT. While RE expressed as caloric unit cost is normalized to speed as it is expressed in kcal $\cdot kg^{-1} \cdot km^{-1}$, GCT and cadence are not, and these variables do change with running speed for an individual runner. Therefore, we do not mean to discount the importance of these variables on RE as has been previously reported (2, 11).

While this is a limitation in interpreting the GCT and cadence data, GCT imbalances were not different across speeds for a particular runner. This is in keeping with previous research showing that running speed had only small effects on other kinetic asymmetries (7). Furthermore, we have shown that the speed at which RE was tested across the runners was not related to RE for the group. Therefore, we feel that despite this limitation, the current findings still present a novel and strong predictor of RE in GCT imbalances.

Impaired RE has also been linked to different indices of excess VO (2, 18). We did not find the VO ratio to be a significant predictor of RE. While VO also increases with faster running speeds, we present the VO ratio as the ratio of VO to stride length. Despite this normalization to stride length/speed, we still did not see a significant relationship between the VO ratio and RE. While we have relied on a simple ratio of VO to stride length, previous research linking excess VO to impaired RE actually measured stride angle by geometrically determining the tangent to the arc of the foot in relation to stride height and length (18). These differences in quantifying VO could explain the inconsistencies in the findings.

We acknowledge that correlations should be interpreted with some caution with smaller sample sizes. Given a sample size of 11 subjects in the present study, we have provided the 95% confidence interval for the significant correlation between GCT imbalances and RE. Additionally, visual inspection of the relationship (Figure 1A) does not suggest that 1 or 2 outliers is driving the relationship observed in the present sample. For this reason, while we acknowledge the limited sample size, we feel these data have merit given this evidence and the novelty of the population and the lack of GCT imbalance or other asymmetry data previously reported in the literature.

A final limitation is that the running dynamics data in the present study were collected with a consumer wearable device, and not a motion capture system. As previously mentioned, the device used in this study has been validated for cadence, VO, and GCT (1). While we acknowledge this as a limitation, we believe that because these running dynamics variables can be easily measured with a consumer device also increases the applicability and utility of the present findings.

It seems reasonable that mechanical imbalances, defined in the current study as GCT imbalances, might negatively impact RE. However, while this relationship is strong in the present sample, we cannot state or conclude a causal link between the variables. Even if we could manipulate GCT imbalances experimentally to demonstrate a causal link to impaired RE, there is likely some other variable related to the GCT imbalances that is causing the impairment. Predictive modeling has suggested that minimizing muscle activation may improve economy and decrease the cost of transport when running (10). Perhaps, the GCT imbalances observed presently are also related to greater muscle activation, or even recruitment of less efficient muscle fibers. Future research might look at electromyography (EMG) in selected muscles to determine differences in recruitment patterns in relation to mechanical imbalances and economy. Additionally, decreased leg stiffness has been linked to increased GCT and impaired RE (12), so perhaps the discrepancies in GCT balance are a result of leg stiffness asymmetries.

Previous research has indicated that leg length discrepancies 2 cm and greater impair running economy (8). In the present study, leg length asymmetries were not strongly related to running economy or GCT imbalances. This is likely due to the fact that leg length asymmetries were minimal, with only one subject with a leg length difference of slightly greater than 1 cm. It was also previously shown that gait asymmetries in able-bodied individuals were more pronounced in subjects with >1 cm leg length asymmetries (19). We also looked at muscle mass imbalances between legs in relation to GCT imbalances. While there were no significant correlations, we did show that the more economical runners in the group had smaller leg lean mass differences than the less economical runners. As previously stated, measurement of EMG might help to determine if muscle mass discrepancies result in altered levels of recruitment that may be linked to poorer economy. While the literature is sparse when comparing muscle mass imbalances between legs to running economy, it has been shown that imbalances between flexor/extensor strength for a given leg might impact economy. In regards to knee flexion/extension, it was shown that higher hamstring to quadriceps peak torque ratios was associated with improved economy (22). Also with hip flexion/extension, stronger hip flexors have been linked to improved economy (21). It is unknown if the GCT imbalances observed in the present study are linked to functional strength imbalances. Because prior exercise has shown to have small effects on regional body composition (13), we acknowledge conducting the DEXA scans following the GXT as a potential limitation.

In conclusion, we have presented evidence that GCT imbalances are related to impaired RE in NCAA Division I distance runners. Because RE is considered a strong predictor of endurance exercise performance, these findings have significant application to coaches and competitive athletes. Furthermore, because GCT imbalances can now be tracked by consumer wearable devices, these findings extend to the broader endurance exercise population. Future research should work to determine the cause of GCT imbalances, if and how they can be corrected, and if this results in improved RE and performance.

ACKNOWLEDGEMENTS

The authors report no funding sources or conflicts of interest.

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