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RESEARCH ARTICLE

The metabolic cost of human running: is swinging the arms worth it?

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ABSTRACT

Although the mechanical function is quite clear, there is no consensus regarding the metabolic benefit of arm swing during human running. We compared the metabolic cost of running using normal arm swing with the metabolic cost of running while restricting the arms in three different ways: (1) holding the hands with the arms behind the back in a relaxed position (BACK), (2) holding the arms across the chest (CHEST) and (3) holding the hands on top of the head (HEAD). We hypothesized that running without arm swing would demand a greater metabolic cost than running with arm swing. Indeed, when compared with running using normal arm swing, we found that net metabolic power demand was 3, 9 and 13% greater for the BACK, CHEST and HEAD conditions, respectively (all $P<0.05$). We also found that when running without arm swing, subjects significantly increased the peak-to-peak amplitudes of both shoulder and pelvis rotation about the vertical axis, most likely a compensatory strategy to counterbalance the rotational angular momentum of the swinging legs. In conclusion, our findings support our general hypothesis that swinging the arms reduces the metabolic cost of human running. Our findings also demonstrate that arm swing minimizes torso rotation. We infer that actively swinging the arms provides both metabolic and biomechanical benefits during human running.

KEY WORDS: Energetics, Locomotion, Upper body rotation, Biomechanics

INTRODUCTION

Humans naturally swing their arms while running, leading one to imagine that there might be an underlying benefit to this behavior. Both Hinrichs (Hinrichs, 1987) and Hamner et al. (Hamner et al., 2010) identified that the primary function of arm swing during distance running is to counterbalance the angular momentum generated by the swinging legs about the vertical axis, resulting in a net vertical angular momentum that fluctuates with a relatively low magnitude about zero. Much earlier, Hopper (Hopper, 1964) speculated that in addition to helping maintain posture and balance, arm swing might assist with increasing the vertical ground reaction force to lift the runner, thus bouncing off the ground more quickly. Hinrichs et al. (Hinrichs et al., 1987) supported Hopper's speculation, finding that arm swing provides a small contribution (~5–10%) to the vertical impulse of the whole body's center of mass (COM). However, more recently, Hamner et al. (Hamner et al., 2010) concluded that arm swing contributes less than 1% of the total COM acceleration.

Although the mechanical benefit is quite clear, the question remains: is there a metabolic benefit to swinging the arms during human distance running? Several studies have compared the metabolic cost of running with and without arm swing, albeit with different methods of restricting arm swing (Arellano and Kram, 2011; Arellano and Kram, 2012; Egbuonu et al., 1990; Pontzer et al., 2009; Tseh et al., 2008). Egbuonu et al. (Egbuonu et al., 1990) reported that when compared with running using normal arm swing, there was an ~4% increase in the rate of oxygen consumption, $\dot{V}_{O_2}$, when subjects ran with their hands held behind their back in a relaxed manner. In this condition, the hands were held at or below the lumbar region (P. R. Cavanagh, personal communication). In contrast, Tseh et al. (Tseh et al., 2008) found that gross $\dot{V}_{O_2}$ was not significantly different whether runners swung their arms normally (43.4 ± 2.6 ml O_2 kg^{-1} min^{-1}) or when they clasped their hands behind the back (43.9 ± 2.4 ml O_2 kg^{-1} min^{-1}). At the extreme, they found that gross $\dot{V}_{O_2}$ was ~6% greater when subjects clasped their hands on top of the head (46.1 ± 2.0 ml O_2 kg^{-1} min^{-1}). With a different approach to removing the effects of arm swing, Pontzer et al. (Pontzer et al., 2009) reported that the net $\dot{V}_{O_2}$ during running was equivalent when swinging the arms normally (37.8 ± 7.2 ml O_2 kg^{-1} min^{-1}) and when voluntarily holding the arms across the chest (37.8 ± 7.2 ml ml O_2 kg^{-1} min^{-1}). In contrast to Pontzer et al. (Pontzer et al., 2009), we found in two independent studies that the metabolic cost of running with the arms held across the chest was ~8% greater than running with normal arm swing (Arellano and Kram, 2011; Arellano and Kram, 2012). The different methods of arm swing restriction used in these various experiments leaves the metabolic benefits of arm swing during human running an unresolved issue.

The main purpose of this study was to re-examine the effects of arm swing on the metabolic cost of human running and to seek the biomechanical basis for any greater cost associated with arm swing restriction. In following Musgrave's (Musgrave, 1974) philosophical examination on hypothesis confirmation, Rowbottom and Alexander (Rowbottom and Alexander, 2012) point out that a true test of a scientific hypothesis is one where the experimenter who performs the experiment is sincerely trying to falsify their hypothesis. Thus, we thought it worthwhile to re-test our hypothesis that arm swing reduces the metabolic cost of running (Arellano and Kram, 2011; Arellano and Kram, 2012) because we had only studied one condition of running without arm swing. It may be that previous studies, including our own, artificially elevated the cost of running because of the extra muscular effort required to hold the arms across the chest. To address these issues, we compared the metabolic cost of running using normal arm swing with the metabolic cost of running while restricting the arms in three different ways: (1) holding the hands with the arms behind the back in a relaxed position (BACK), (2) holding the arms across the chest (CHEST) and (3) holding the hands on top of the head (HEAD; Fig. 1). In our genuine attempt at refutation, we reasoned that holding the hands with the arms behind the back in the most relaxed position would

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give us the best chance of falsifying our human running arm swing hypothesis.

In keeping with our original thinking, we hypothesized that running without arm swing would demand a greater metabolic cost than running with normal arm swing (Arellano and Kram, 2011; Arellano and Kram, 2012). We also explored whether subjects increase and/or modify torso rotation when arm swing is restricted, as this would provide the most plausible explanation for an increase in the metabolic cost of running (Arellano and Kram, 2012).

RESULTS
Effects of arm swing on net metabolic power
The rates of metabolic energy consumption were greater when subjects ran without arm swing. Compared with running using normal arm swing, the demand for net metabolic power was 3, 9 and 13% greater when running with the arms in the BACK, CHEST and HEAD conditions, respectively (all $P<0.05$; Fig. 2, Table 1). Even in the least demanding no-arm-swing condition (BACK), 10 out of 13 subjects consumed metabolic energy at a faster rate when compared with running using normal arm swing (Table 2). Note that the respiratory exchange ratios (RERs) for all trials were <1.0, suggesting that metabolic energy was provided primarily by aerobic metabolism.

Effects of arm swing on shoulder and pelvis rotation
Subjects increased the peak-to-peak amplitudes of both shoulder and pelvis rotation about the vertical axis when running without arm swing (Fig. 3). When compared with running using normal arm swing, the peak-to-peak amplitude of shoulder rotation about the vertical axis increased by 10% (BACK, $P<0.05$) and 44% (CHEST, $P<0.01$). Peak-to-peak amplitude of shoulder rotation increased numerically by 8% when running in the HEAD condition, but the difference was not statistically significant ($P=0.08$). The peak-to-peak amplitude of pelvis rotation about the vertical axis also increased by 63% (BACK), 102% (CHEST) and 101% (HEAD) when compared with running using normal arm swing (all $P<0.01$).

Effects of arm swing on step frequency
When compared with normal arm swing, subjects increased their step frequency by 2.5% (BACK), 2.9% (CHEST) and 4.3% (HEAD) when arm swing was restricted during running (all $P<0.01$; Table 1).

DISCUSSION
In support of our running arm swing hypothesis, the demand for net metabolic power increased when running without arm swing. Even in our best attempt at refutation, we found that while running with
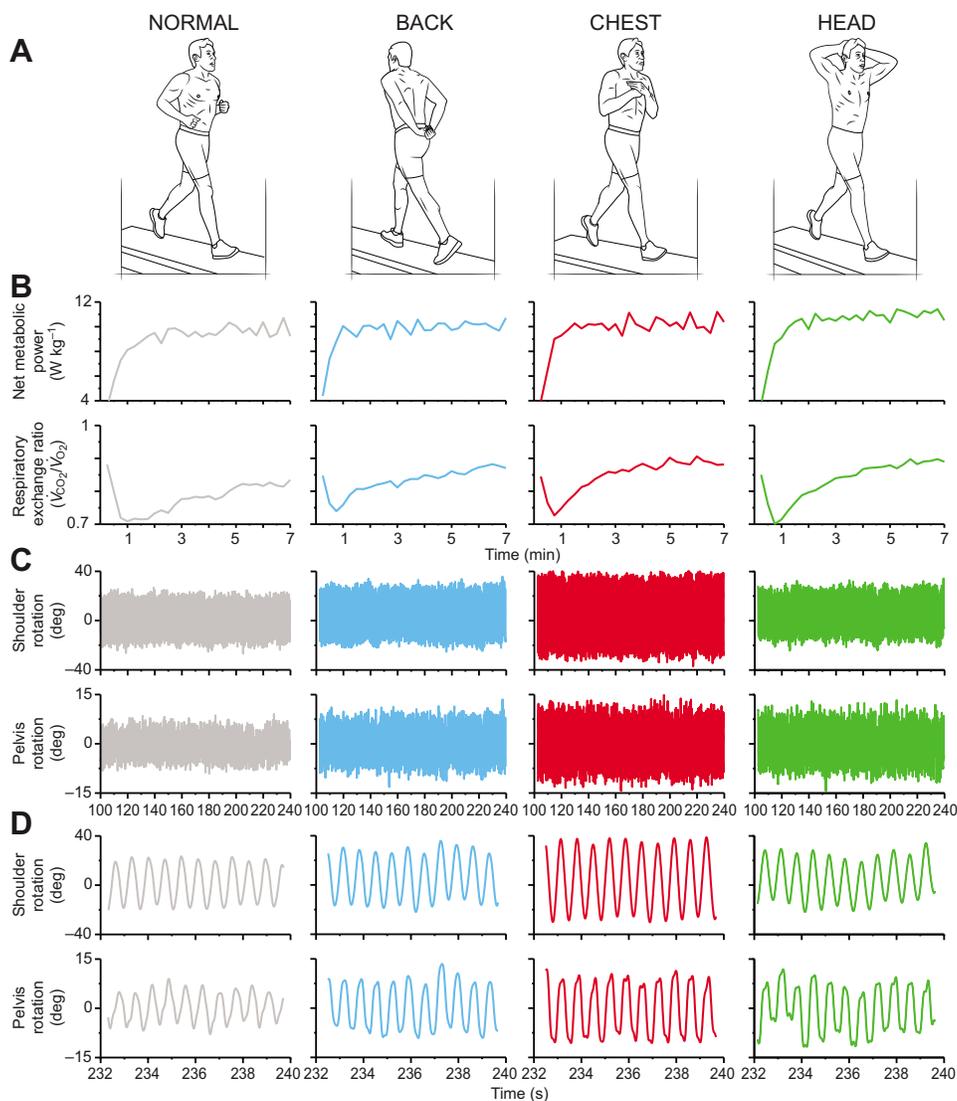

Fig. 1. The metabolic cost and upper body kinematics of running with and without arm swing. (A) On the first day, subjects were asked to run on a force-measuring treadmill while: swinging their arms normally (NORMAL), holding the hands with the arms behind the back in a relaxed position (BACK), holding the arms across the chest (CHEST), and holding the hands on top of the head (HEAD) as we collected rates of oxygen consumption and carbon dioxide production. (B) From these data, we calculated net metabolic power demand and the respiratory exchange ratio. On the second day, subjects repeated these conditions while we collected the 3D position data for markers placed on the body. (C) The traces represent typical time series data for shoulder and pelvis rotation during the last 401 consecutive steps for each 7 min running trial. (D) Exploded view of the typical time series data for shoulder and pelvis rotation during the last 8 s of each 7 min running trial. Running illustrations by René Cárdenas, Design Con Safos.

Table 1. Average data for subjects running (3 m s⁻¹) under various conditions: normal arm swing (NORMAL), holding the hands with the arms behind the back in a relaxed position (BACK), holding the arms across the chest (CHEST), and holding the hands on top of the head (HEAD)

	Condition			
	NORMAL	BACK	CHEST	HEAD
Net metabolic power (W kg⁻¹)	9.84±0.17	10.12±0.10*	10.71±0.14**	11.15±0.17**
RER ($\dot{V}_{CO_2}/\dot{V}_{O_2}$)	0.87±0.01	0.89±0.01*	0.89±0.01*	0.91±0.01***
Shoulder rotation (deg)	32.40±1.80	35.61±1.72*	46.67±2.46**	35.11±1.49
Pelvis rotation (deg)	8.05±0.69	13.11±1.03**	16.30±1.53**	16.25±1.05**
Step frequency (Hz)	2.80±0.04	2.86±0.04**	2.87±0.04**	2.91±0.05**

Values are expressed as means ± s.e.m. Statistical comparisons are against the NORMAL condition, i.e. running with arm swing. *$P<0.05$; **$P<0.01$; ***$P<0.001$.

RER, respiratory exchange ratio.

the hands held in a relaxed position behind the lower back, the demand for net metabolic power increased by 3%. As expected, the more restricted arm swinging conditions progressively increased the metabolic cost of running. Overall, we believe that our comprehensive approach to testing our running arm swing hypothesis provides the most conclusive evidence to date that arm swing provides a metabolic benefit during human running.

Our net metabolic power results are in agreement with those of Egbuonu et al. (Egbuonu et al., 1990), who found that running with the arms held behind the back significantly increased $\dot{V}_{O_2}$. However, Tseh et al. (Tseh et al., 2008) found that the gross $\dot{V}_{O_2}$ values for running were not different between swinging the arms normally and holding the arms behind the back. In addition, our results are also in disagreement with those of Pontzer et al. (Pontzer et al., 2009), who found that the net $\dot{V}_{O_2}$ during running was similar when swinging the arms normally or holding the arms across the chest. In our CHEST condition, we found a 9% increase in net metabolic power during running, which is in close agreement with the 8% increases we found previously (Arellano and Kram, 2011; Arellano and Kram, 2012). What could explain the discrepancy between our results and

those of Tseh et al. (Tseh et al., 2008) and Pontzer et al. (Pontzer et al., 2009)?

We propose two possible reasons: (1) low sample size and (2) oxygen cost measurements alone do not take into account energy substrate utilization. As noted previously (Arellano and Kram, 2012), Pontzer et al. (Pontzer et al., 2009) measured oxygen consumption for a subset of only six subjects, most likely resulting in low statistical power. Tseh et al. (Tseh et al., 2008) had a sample size of nine, which should be adequate power to detect small differences between arm-swing and arms-behind-the-back conditions. However, measurements of oxygen consumption alone may not be adequate to detect small differences between arm swing and no arm swing conditions. In fact, when we statistically compare our conditions using only the gross rate of oxygen consumption [the same units as Tseh et al. (Tseh et al., 2008)], running with normal arm swing (33.1±0.6 ml O_2 kg⁻¹ min⁻¹) was not significantly different from running with the arms held behind the back (33.7±0.4 ml O_2 kg⁻¹ min⁻¹; $P=0.07$). Consistent with our net metabolic power results, the gross $\dot{V}_{O_2}$ while running with the arms across the chest (35.4±0.5 ml O_2 kg⁻¹ min⁻¹; $P<0.001$) and running
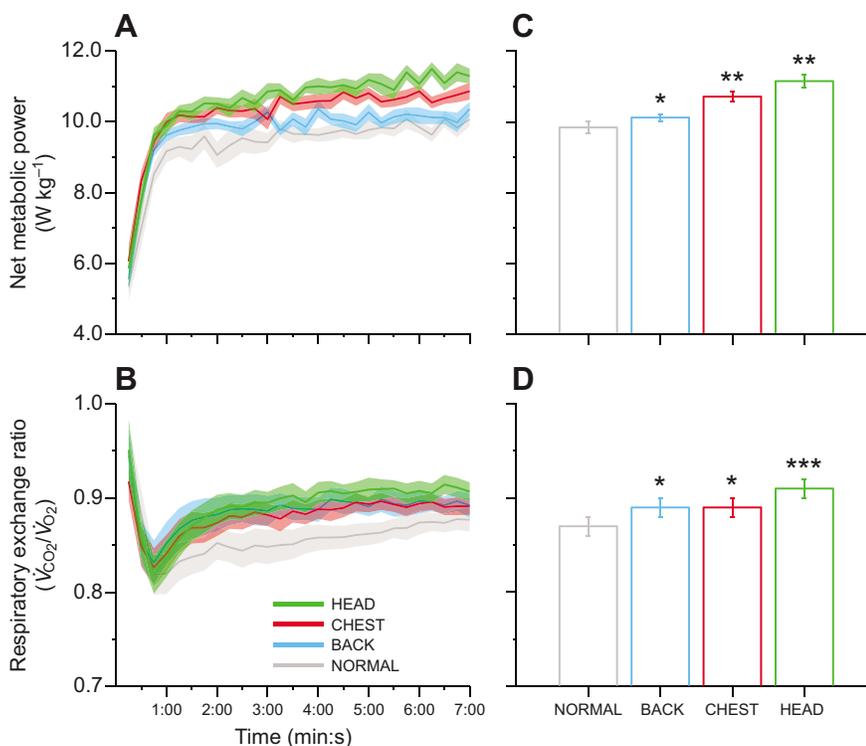

Fig. 2. Arm swing provides a metabolic benefit during human running. (A,B) Average time-series course for (A) net metabolic power demand and (B) respiratory exchange ratio during running. Each line represents the mean time course over the 7 min running trial and the shaded region represents ±s.e.m. (C,D) Mean (±s.e.m.) value for (C) net metabolic power demand and (D) respiratory exchange ratio computed from the last 3 min of each 7 min running trial (n=13). Statistical comparisons are against the NORMAL condition, i.e. running with arm swing (*$P<0.05$; **$P<0.01$; ***$P<0.001$).

Table 2. Subject characteristics and data values for net metabolic power demand (W kg⁻¹) and respiratory exchange ratio (RER) for each individual running with and without arm swing at 3 m s⁻¹

Subject	Sex (M/F)	Age (yr)	Mass (kg)	NORMAL W kg^{-1}	RER	BACK W kg^{-1}	RER	CHEST W kg^{-1}	RER	HEAD W kg^{-1}	RER
1	M	27	80.91	10.01	0.84	10.03	0.96	11.14	0.89	11.19	0.96
2	M	23	66.82	10.32	0.91	10.06	0.87	11.01	0.88	10.74	0.90
3	M	25	78.18	10.61	0.86	10.96	0.90	11.67	0.86	12.00	0.88
4	M	26	77.16	10.85	0.84	10.24	0.90	10.94	0.89	12.40	0.93
5	F	31	55.45	9.75	0.81	10.09	0.86	10.27	0.89	11.02	0.88
6	M	27	83.64	9.47	0.89	10.03	0.94	10.45	0.89	10.98	0.95
7	F	31	57.27	9.69	0.84	10.43	0.83	11.20	0.85	11.39	0.88
8	M	23	53.86	9.86	0.85	9.86	0.86	10.72	0.86	11.03	0.87
9	M	30	80.91	8.70	0.87	9.71	0.89	9.97	0.92	10.82	0.93
10	F	21	57.05	9.57	0.85	9.84	0.86	10.55	0.90	10.77	0.88
11	M	26	71.93	10.41	0.96	10.61	0.96	11.03	0.96	11.85	0.97
12	F	27	52.05	9.35	0.91	9.81	0.93	9.85	0.94	10.48	0.93
13	F	20	63.18	9.29	0.84	9.88	0.89	10.40	0.87	10.28	0.86

with the hands on top of the head (36.6 ± 0.5 ml O$_2$ kg^{-1} min^{-1}; $P<0.001$) were significantly greater than running with normal arm swing.

In our laboratory, we quantify metabolic energy expenditure from rates of both oxygen consumption and carbon dioxide production using the Brockway equation (Brockway, 1987), with the assumption that protein metabolism is nil. The Brockway equation calculates energy expenditure by taking into account the type of energy substrate utilized, i.e. the energy liberated in the metabolism of the physiological fuels carbohydrates and fat. Fletcher et al. (Fletcher et al., 2009) recently presented compelling evidence that running economy values are more sensitive to changes in speed when accounting for substrate utilization via the RER as opposed to relying on rates of oxygen consumption alone. Indeed, we observed a significant increase in the RER in the no-arm-swing conditions (Fig. 2). On average, the RER was greater when running without arm swing, indicating a shift to more carbohydrate and less fat

utilization. What is the advantage of changing RER with respect to the more demanding condition of running without arm swing? Oxidizing carbohydrates rather than fat yields more energy per unit of O$_2$ consumed (Brooks et al., 2004), a change that has the advantage of meeting the greater demand when the arms are restricted from swinging.

Even when we computed the demand for net metabolic power in W kg^{-1}, running with the arms held behind the back was slightly cheaper for two subjects. Curious as to why this might have occurred, and knowing that some runners have unusual arm swinging styles, we compared the style of arm swing motion for each runner. We studied digitized videos produced by our motion analysis software and found that all subjects in this study adopted a style characterized by swinging the arms back and forth, with a slight crossover in front of the torso. This type of crossover style has been suggested to reduce the side-to-side motion of the whole-body COM during human running (Hinrichs et al., 1987). The style of
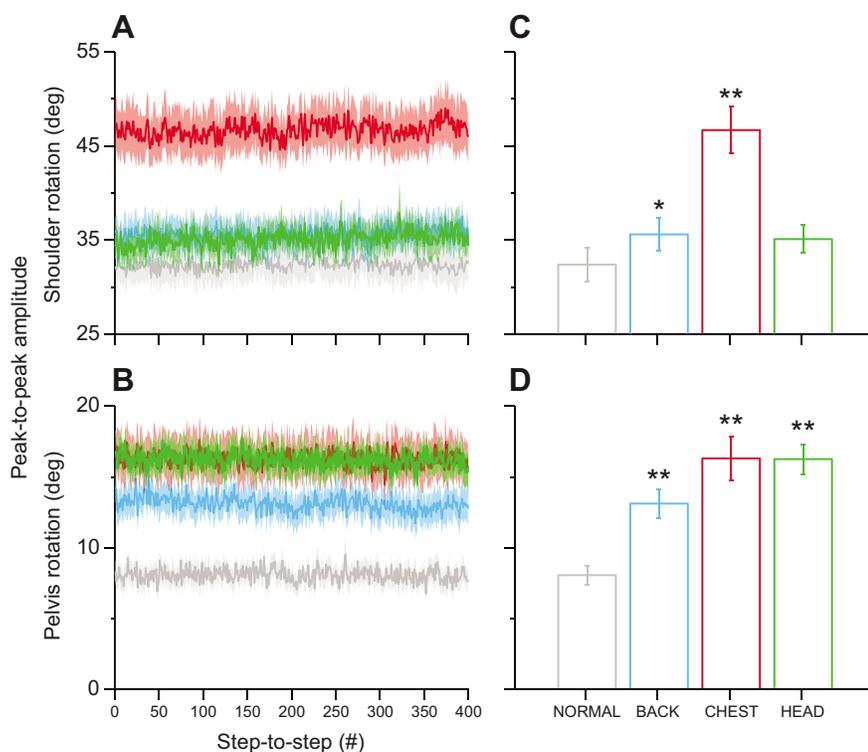

Fig. 3. Arm swing reduces the peak-to-peak amplitude of shoulder and pelvis rotation during human running. (A,B) Peak-to-peak amplitude of shoulder (A) and pelvis (B) rotation from step-to-step (#). Each line represents the mean peak-to-peak amplitude during last 401 consecutive steps during each running trial, and the shaded region represents the ±s.e.m. (C,D) Mean (±s.e.m.) value for the peak-to-peak amplitude of shoulder (C) and pelvis (D) rotation computed from the last 401 consecutive steps for each running trial ($n=13$). Statistical comparisons are against the NORMAL condition, i.e. running with arm swing (*$P<0.05$; **$P<0.01$).

arm swing does not appear to explain why two subjects used less metabolic energy to run with their hands held behind their backs. In the future, a more rigorous mechanical analysis of the individual styles of arm swing may be useful for explaining this phenomenon.

Confirming our previous speculation about torso motion when running without arm swing (Arellano and Kram, 2012), we found that subjects significantly increased the peak-to-peak amplitude of both shoulder and pelvis rotation (Fig. 3). Our findings support the idea that arm swing helps to minimize torso rotation. In the absence of arm swing during running, increasing the peak-to-peak amplitude of both shoulder and pelvis rotation is most likely a compensatory strategy to counterbalance the rotational angular momentum of the swinging legs (Miller et al., 2009). This strategy apparently exacts a greater metabolic cost than swinging the arms because greater activation of trunk muscles would be required to actuate and control the rotation of the torso, which accounts for ~40–50% of the total body mass, while both arms account for ~10% of the total body mass (Pearsall et al., 1996; Winter, 1990). In addition, the compensatory strategy of increasing torso rotation may explain why the free vertical moment did not increase when arm swing was restricted in the running study of Miller et al. (Miller et al., 2009).

If arm swing provides a metabolic benefit of at most 3%, it begs the hypothetical question: would human distance running be metabolically cheaper without the extra mass of the arms? During running, the demand for net metabolic power is almost proportional to added mass (Taylor et al., 1980; Teunissen et al., 2007). Therefore, if both arms comprise ~10% of the total body mass, the demand for net metabolic power would be reduced by ~10% as a result of carrying less mass without the arms. From this macabre algebraic logic, one could conclude that when running without the added mass of the arms, humans could reduce their metabolic cost and thus enhance distance running economy by ~7%. Yet, removing the arms could lead to compensatory strategies that exact a metabolic cost. As Hinrichs (Hinrichs, 1987) discovered, the momentum effects of arm swing are due to the relatively longer distance of the arm's COM from the vertical axis, acting to generate the largest component of the vertical angular momentum of the entire upper body, which includes the head and trunk. Although the momentum effects of arm swing reduce the amount of torso rotation, there is likely a small cost resulting from the tonic muscular activity required to hold the arms in a flexed position at the elbow, a common style of swinging the arms during human running. The small cost of holding the arms in a flexed position at the elbow is presumably subsumed by the metabolic energy saved by reducing torso rotation. While our metabolic results have allowed direct comparison with previous experiments, an additional condition in which the arms were supported in elbow-flexed positions by lightweight slings may have provided more insight. The major point is that the total absence of the arms would likely require an even greater torso rotation to counterbalance the vertical angular momentum of the swinging legs, possibly counteracting the metabolic savings of arm swing. A study of Paralympic athletes who congenitally lack arms or who have had arm amputations might provide more insight into the effects of no arm swing during human running. While our results highlight the benefit of arm swing during distance running, human arm swing during sprinting might serve a different function, where acceleration and maximizing power output, and not minimizing metabolic energy cost, are of primary importance.

The present study reveals some limitations about our previous work studying arm swing during human running (Arellano and Kram, 2011; Arellano and Kram, 2012). In those two studies, we compared the metabolic cost of running at 3 m s^{-1} with and without arm swing. When running without arm swing, subjects held their arms across the chest as illustrated in Fig. 1A. We found that running without arm swing increased net metabolic power demand by ~8%; however, we now feel that estimate was methodologically misleading. When compared with running with the arms behind the back, running with the arms held across the chest demands ~5–6% more net metabolic power. This increased demand is most likely due to a combination of greater muscular effort to: (1) hold the arms in a fixed position across the chest and (2) increase upper body rotation as a compensatory strategy to counterbalance the vertical angular momentum of the swinging legs. With respect to our kinematic measurements, it is possible that the reflective markers placed above the skin of the acromion processes may have slightly shifted when restricting the arms in the different conditions. Therefore, a misalignment may have occurred between the position of the reflective marker and the acromion processes. However, any such misalignments would not have affected our peak-to-peak amplitude measures. Another possible limitation of our study is that we did not control for step frequency across arm-swing and no-arm-swing conditions. However, based on the regression equations of Snyder and Farley (Snyder and Farley, 2011), increases in step frequency of 2.5% (BACK), 2.9% (CHEST) and 4.3% (HEAD) would increase the demand for net metabolic power by less than 0.6, 0.8 and 1%, respectively, thereby having little influence on our metabolic results. Further, we suspect that the changes in step frequency were adaptive (i.e. minimizing metabolic cost) rather than maladaptive.

In summary, we find that arm swing reduces the demand for net metabolic power during human distance running. We also find that when arm swing is restricted, subjects increase the peak-to-peak amplitude of both shoulder and pelvis rotations, which likely explains the greater demand for net metabolic power. Our data suggest that actively swinging the arms provides both metabolic and biomechanical benefits during human distance running.

MATERIALS AND METHODS

Thirteen subjects participated in this study (eight men and five women, age=25.9±3.5 years, mass=67.57±11.73 kg, height=1.77±0.09 m, mean ± s.d.). All subjects wore their own running shoes, were healthy, recreational/competitive runners, had no current injuries and were experienced with treadmill running. As part of our inclusion criteria and to ensure that our experimental protocol required a light to moderate running intensity, we recruited subjects that were comfortable running at an ~08:30 minute/mile pace (3.2 m s^{-1}) for 45 min without rest. Prior to experimental data collection, each subject read and signed an informed consent document approved by the University of Colorado Institutional Review Board.

Subjects visited the laboratory on two separate days. The first day was dedicated to metabolic measurements in which we are able to reliably discern small metabolic differences between running conditions (Arellano and Kram, 2012; Franz et al., 2012; Tung et al., 2014). Subjects first stood quietly for 7 min while we measured their rates of oxygen consumption ($\dot{V}_{O_2}$) and carbon dioxide production ($\dot{V}_{CO_2}$) using expired gas analysis (ParvoMedics TrueMax2400, Sandy, UT, USA). Following the standing trial, we measured $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ while subjects completed four randomized 7 min running trials at 3 m s^{-1} on a force-measuring treadmill (Kram et al., 1998) that included normal arm swing (NORMAL) and the arms in the BACK, CHEST or HEAD conditions (Fig. 1). To reduce any effects of fatigue, subjects were allowed a full recovery *ad libitum* with at least 5 min between each running trial. Based on self-reports during the screening process, subjects regularly trained at a mean running pace of 3.6±0.3 m s^{-1} while covering a distance of 54.7±16.9 km week^{-1} (mean ± s.d.). Therefore, running at 3 m s^{-1} for a total of 28 min with rest intervals during our experiment fell well within a submaximal running intensity for all subjects.

On the second day, subjects repeated each 7 min running trial, again in a random order, while we simultaneously collected ground reactions forces/moments (1000 Hz) and upper/lower body kinematics (100 Hz) from the 3D positions of reflective markers placed on the body during the last 4 min of each trial (eight-camera system, Motion Analysis Corporation, Santa Rosa, CA, USA). Because our secondary aim was to explore modifications to upper body motion, we focused our kinematic data analysis on the reflective markers placed on the shoulders and pelvis. We carefully palpated the shoulder region to ensure that the reflective markers were rigidly attached to the skin above each acromion process using adhesive tape. Before and after every running trial, we checked that the reflected markers had not shifted or become loose when the arms were held in the different conditions. Note that we performed the metabolic and kinematic measurements on separate days because the inspired and expired metabolic gas hoses blocked some of the motion capture cameras from viewing the reflective markers.

Data analysis

As previously described (Arellano and Kram, 2011; Arellano and Kram, 2012), we calculated net metabolic power from the average $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ during the last 3 min of each trial using the Brockway equation (Brockway, 1987). From the filtered position data of the reflective markers (Arellano and Kram, 2011; Arellano and Kram, 2012), we calculated time series data for shoulder and pelvis rotations in the transverse plane, i.e. about the vertical axis. We defined the shoulder and pelvis from the position of reflective markers placed on the left and right acromion and the left and right anterior superior iliac spine, respectively. We subtracted the angular position of the shoulder and pelvis segments calculated from a 5 s standing calibration from each running trial. The standing calibration was collected to 'zero' the anatomical reference system for each segment. The location of the markers during the standing calibration trial was used to correct for any misalignment of the local reference vectors that defined the shoulder and pelvis segment (Arellano et al., 2009). By determining the instants of initial contact using vertical ground reaction force data (Arellano and Kram, 2011), we computed the peak-to-peak amplitude of shoulder and pelvis rotation from step to step during the last 401 consecutive steps for each trial. We performed our kinematic analysis over the last 401 consecutive steps to keep consistent with our previous methods (Arellano and Kram, 2011; Arellano and Kram, 2012).

Statistical analysis

We performed a repeated-measures ANOVA with planned comparisons between normal arm-swing (the control; NORMAL) and no-arm-swing conditions (BACK, CHEST and HEAD) using Dunnett's multiple comparison method and published data table for a one-sided comparison against a control (Dunnett, 1955; Dunnett, 1964) (Table 1). All values are reported as means ± s.e.m. unless otherwise noted.

Author contributions

Both authors contributed to the conception, design and execution of the experiments, interpretation of the data, and writing and editing the article.

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