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Paper:

McNarry, M., Wilson, R., Holton, M., Griffiths, I. & Mackintosh, K. (2017). Investigating the relationship between energy expenditure, walking speed and angle of turning in humans. *PLOS ONE*, 12(8), e0182333

<http://dx.doi.org/10.1371/journal.pone.0182333>

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RESEARCH ARTICLE

Investigating the relationship between energy expenditure, walking speed and angle of turning in humans

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Abstract

Recent studies have suggested that changing direction is associated with significant additional energy expenditure. A failure to account for this additional energy expenditure of turning has significant implications in the design and interpretation of health interventions. The purpose of this study was therefore to investigate the influence of walking speed and angle, and their interaction, on energy expenditure in 20 healthy adults (7 female; 28±7 yrs). On two separate days, participants completed a turning protocol at one of 16 speed- (2.5, 3.5, 4.5, 5.5 km·h⁻¹) and angle (0, 45, 90, 180°) combinations, involving three minute bouts of walking, interspersed by three minutes seated rest. Each condition involved 5 m of straight walking before turning through the pre-determined angle with the speed dictated by a digital, auditory metronome. Tri-axial accelerometry and magnetometry were measured at 60 Hz, in addition to gas exchange on a breath-by-breath basis. Mixed models revealed a significant main effect for speed ($F = 121.609$, $P < 0.001$) and angle ($F = 19.186$, $P < 0.001$) on oxygen uptake ($\dot{V}O_2$) and a significant interaction between these parameters ($F = 4.433$, $P < 0.001$). Specifically, as speed increased, $\dot{V}O_2$ increased but significant increases in $\dot{V}O_2$ relative to straight line walking were only observed for 90° and 180° turns at the two highest speeds (4.5 and 5.5 km·hr⁻¹). These findings therefore highlight the importance of accounting for the quantity and magnitude of turns completed when estimating energy expenditure and have significant implications within both sport and health contexts.

OPEN ACCESS

Citation: McNarry MA, Wilson RP, Holton MD, Griffiths IW, Mackintosh KA (2017) Investigating the relationship between energy expenditure, walking speed and angle of turning in humans. PLoS ONE 12(8): e0182333. <https://doi.org/10.1371/journal.pone.0182333>

Editor: Luca Paolo Ardigo, Universita degli Studi di Verona, ITALY

Received: February 3, 2017

Accepted: July 17, 2017

Published: August 10, 2017

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Data Availability Statement: All relevant data are within the paper and its Supporting Information files.

Funding: The author(s) received no specific funding for this work.

Competing interests: The authors have declared that no competing interests exist.

Introduction

A high body mass index is a major risk factor for the incidence of numerous non-communicable diseases (NCD), such as cardiovascular and kidney diseases, diabetes and some cancers [1–6]. Indeed, obesity has been recognised as a major public health challenge for the 21st century [7], with concerns regarding the health and economic burden, which have led to the identification of global targets to halt the rise in obesity prevalence by 2025 [8, 9]. However, recent figures

from the NCD Risk Factor Collaboration, which analysed the aggregated data of 19.2 million participants from 200 countries, suggest that if current, post-2000, trends continue, the probability of meeting these targets is almost zero. These findings highlight the critical need to develop and implement effective interventions for the prevention and treatment of excess body mass [10]. A fundamental principle in the development of such interventions is the assessment of the energy expenditure associated with activities of daily living; weight management strategies are most effective when individuals can accurately determine how much energy they have expended [11]. Indeed, a failure to assess energy expenditure appropriately may, at least in part, explain the inconsistent evidence regarding intervention effectiveness and sustainability.

Walking represents a popular, convenient and relatively safe form of activity that can easily be incorporated into weight management programmes [12–14]. The energy expenditure associated with walking are reported to be either linearly or slightly exponentially related to speed [15]. However, the applicability of these findings is based on walking in a straight line which does not align with everyday activities. In particular, recent studies have suggested that the process of changing direction is associated with significant additional energy expenditure [16–18]. Wilson et al. [18] reported that the energy expenditure of turning is linearly related to the degree of turning angle at $6 \text{ km}\cdot\text{hr}^{-1}$ while Hatamoto et al. found quadratic [17] or linear [16] functions best represented the relationship between running speed and the energy expenditure of a 180° turn. A failure to account for this additional energy expenditure of turning has significant implications for both sporting and health contexts. For example, most English Premier league footballers make more than 700 turns per match [19] while medical treatment effectiveness is often assessed using a six-minute walking test. While the latter is intended to be conducted over a standardised 30 m straight line distance [20], some studies have used 20 m or 50 m straights [21, 22], significantly influencing the number of turns completed and thus potentially confounding inter-study comparisons. Indeed, the difference in the number of turns completed, and thus overall energy expenditure, may explain studies, which utilised shorter straights reporting significantly shorter distances covered [23–25].

The purpose of the present study was therefore to investigate the influence of walking speed, angle, and their interaction, on energy expenditure. We hypothesised that 1) as walking speed increased, so would energy expenditure; 2) as angle increased, so would energy expenditure and that 3) angle and speed would demonstrate a synergistic effect on energy expenditure while walking.

Materials and methods

Participants

In total, 20 healthy adults (7 female, 13 male; 28 ± 7 yrs; $20.5 \pm 4.1 \text{ kg}\cdot\text{m}^2$) were recruited for the study. The participants were all recreationally active but none were highly trained. Prior to testing, participants were informed of the protocol and risks and provided written consent. All procedures were approved by a Swansea University ethics committee and were conducted in accordance with the Declaration of Helsinki. Participants were asked to arrive at the laboratory in a rested state, at least two hours postprandial and to avoid strenuous exercise in the 24 hours preceding each testing session. Participants were also asked to refrain from caffeine and alcohol for 6 and 24 h before each test, respectively. All tests were performed at the same time of day (± 2 h).

Experimental design

Participants were required to visit the laboratory/indoor track on three occasions, separated by at least 24 hours recovery. Participants initially completed an incremental treadmill test for

determination of peak oxygen uptake ($\dot{V}O_{2\text{peak}}$) and the gas exchange threshold (GET). On each of the two subsequent visits, participants completed the turning protocol.

Incremental treadmill test

Following a three-minute warm-up at $6 \text{ km}\cdot\text{hr}^{-1}$, the treadmill speed increased by $1 \text{ km}\cdot\text{hr}^{-1}$ every minute until participants reached volitional exhaustion. The treadmill gradient was set at 1% throughout the test [26], until participants reached their maximal running speed at which point it subsequently increased by 1% every minute until volitional exhaustion. Participants were given strong verbal encouragement throughout the test.

Turning protocol

On subsequent visits to the indoor track, each participant was asked to complete repeated three-minute bouts of walking interspersed by three minutes of rest. In a randomised order, each participant walked at four different walking velocities ($2.5, 3.5, 4.5, 5.5 \text{ km}\cdot\text{hr}^{-1}$) in combination with four different angles ($0, 45, 90, 180^\circ$). Specifically, each of the sixteen conditions involved 5 m of straight walking interspaced by prescribed turns with the speed dictated by a digital, auditory metronome, which sounded once half-way between turns and once on the turns. Each condition incorporated an equal number of left- and right-handed turns, as illustrated in Fig 1.

Measurements

Throughout all the tests, gas exchange variables (MetaMax Cortex 3B, CORTEX Biophysik GmbH, Germany) were measured on a breath-by-breath basis and displayed online. Prior to

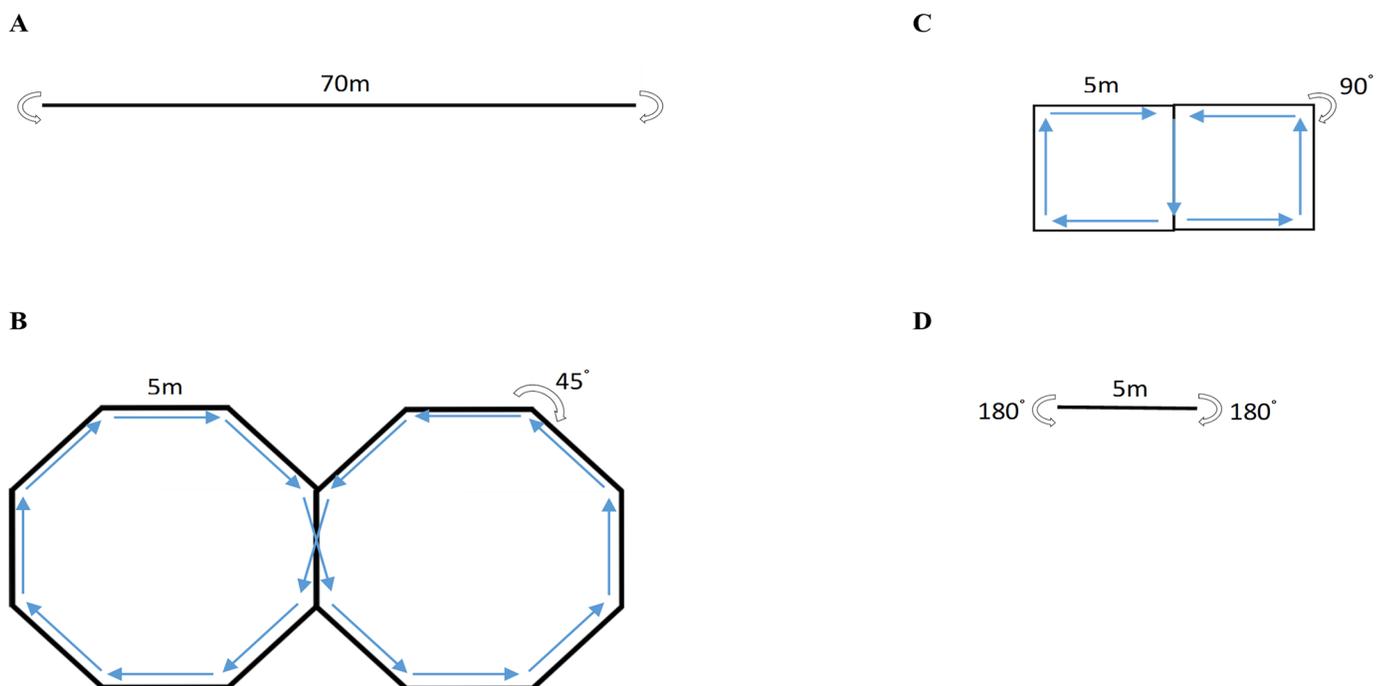


Fig 1. Schematic of the turning protocol showing 5m straights interspersed by prescribed turns of a) 0° b) 45° c) 90° and d) 180° with equal left and right hand turns.

<https://doi.org/10.1371/journal.pone.0182333.g001>

each test, the gas analysers were calibrated using gases of known concentration and the turbine volume transducer was calibrated using a 3-litre syringe (Hans Rudolph, Kansas City, MO). The delay in the capillary gas transit and analyser rise time were accounted for relative to the volume signal, thereby time-aligning the concentration and volume signals. Additionally, two combined tri-axial accelerometers and tri-axial magnetometers (SLAM Tracker, Wildbyte Technologies Ltd, Swansea, UK), measuring at 60 Hz, were worn by participants; one set was worn on the right mid-axilla line at the level of the iliac crest and one set at the middle of the lower back.

Data analysis

The peak $\dot{V}O_2$ was defined as the highest 10 s stationary average during the incremental treadmill test. The GET was determined by the V-slope method [27] as the point at which carbon dioxide production began to increase disproportionately to $\dot{V}O_2$, as identified using purpose written software developed using LabVIEW (National Instruments, Newbury, UK). The mean $\dot{V}O_2$ during each condition was taken as the first 45 seconds of the final minute of that bout. Subsequent analyses were based on the premise that the energy expenditure of turning was superimposed on the baseline energy expenditure of straight line travel. Thus, the difference in $\dot{V}O_2$ during straight line walking (0°) at each speed compared to the $\dot{V}O_2$ engendered during walking with 45, 90 or 180° turns, was attributed to the additional energy expenditure of turning. This $\dot{V}O_2$ was converted to gross energy expenditure in kJ using a conversion factor of 20.1 J per ml of oxygen and subsequently divided by the total number of turns per condition to provide an estimate of the energy expenditure of each angle and speed combination.

The raw accelerometer data were converted to dynamic body acceleration (DBA) by first smoothing each channel to derive the static acceleration using a running mean over 2 s [28] and then subtracting this static acceleration from the raw data [29]. The resulting values for dynamic acceleration were all then converted to positive values. These values for DBA were then vectorially summed to give:

$$VeDBA = \sqrt{(A_x^2 + A_y^2 + A_z^2)}$$

Where $VeDBA$ is the vectorial dynamic body acceleration, A_x , A_y , and A_z are the derived dynamic accelerations at any point in time corresponding to the three orthogonal axes of the accelerometer [30].

Mean and summed $VeDBA$ were derived for each individual turn and straight during the middle minute of the each condition and for the overall three minute bout. Individual turns and straights were determined using custom designed C++ software (DDMT Wildbyte Technologies Ltd) written specifically for the SLAM Tracker devices, to visualise the accelerometry and magnetometry traces and identify the point at which each trace significantly deviated from the local mean.

Statistics

Gaussian distributions in data were confirmed by Shapiro-Wilks tests. To account for the repeated and correlated nature of the data, linear mixed-effects models were used to determine the influence of, and interaction between, walking speed and turn angle on energy expenditure and $VeDBA$ (S1 File). All condition combinations were placed in one model with covariates (sex, stature, peak $\dot{V}O_2$ and/or turning $\dot{V}O_2$ for $VeDBA$) added to subsequent adjusted models to determine their modulatory effect. Pearson product moment correlation coefficients were used to analyse the degree of association between key variables. Statistical analyses were

Table 1. Participant characteristics.

	Total	Male	Female
n	10	13	7
Age, yrs	28.0 ± 6.7	28.5 ± 7.5	27.2 ± 5.3
Stature, m	1.74 ± 0.09	1.78 ± 0.08	1.67 ± 0.02*
Body mass, kg	72.1 ± 16.1	74.5 ± 16.1	67.6 ± 16.4
BMI, kg·m ²	20.6 ± 4.1	20.8 ± 3.9	20.3 ± 4.9
Peak $\dot{V}O_2$, l·min ⁻¹	3.54 ± 0.75	3.92 ± 0.64	2.85 ± 0.33*
Relative peak $\dot{V}O_2$, l·kg ⁻¹ ·min ⁻¹	49.8 ± 7.9	53.2 ± 5.5	43.5 ± 8.1*
GET, l·min ⁻¹	2.31 ± 0.66	2.52 ± 0.71	1.92 ± 0.34*
GET, %	65 ± 9	64 ± 10	67 ± 7

Mean ± SD. BMI, body mass index; $\dot{V}O_2$, oxygen uptake, GET, gas exchange threshold.

* Significant difference between males and females $P < 0.05$

<https://doi.org/10.1371/journal.pone.0182333.t001>

conducted using PASW Statistics 21 (SPSS, Chicago, IL). All data are presented as means ± SD. Statistical significance was accepted when $P \leq 0.05$.

Results

Descriptive characteristics of the sample population are shown in Table 1. The male participants were significantly taller and demonstrated a higher peak $\dot{V}O_2$, both in absolute and relative terms (normalised per kg body mass).

As shown in Table 2, there was a significant main effect for speed ($F = 121.609, P < 0.001$) and turn angle ($F = 19.186, P < 0.001$) on $\dot{V}O_2$ and a significant interaction between these parameters ($F = 4.433, P < 0.001$). Specifically, as speed increased, $\dot{V}O_2$ increased, but significant increases in $\dot{V}O_2$ relative to straight line walking were only observed for 90° and 180° turns at the two highest speeds (4.5 and 5.5 km·hr⁻¹; Table 2). Males demonstrated a significantly greater $\dot{V}O_2$ across all conditions ($F = 25.322, P < 0.001$), although this difference was reversed when stature was included in the model (Sex: $F = 16.77, P < 0.001$; Stature: $F = 152.493, P < 0.001$). $\dot{V}O_2$ during the turning protocol was dependent on peak $\dot{V}O_2$ ($F = 100.970, P < 0.001$) but once scaled to account for differences in body size, this relationship was no longer significant ($F = 0.708, P > 0.05$).

Table 2. Mean energy expenditure and VeDBA during each combination of walking speed and angle.

	$\dot{V}O_2$ (l·min ⁻¹)				Mean VeDBA (g)			
	0°	45°	90°	180°	0°	45°	90°	180°
2.5 km·hr ⁻¹	0.66 ± 0.20	0.63 ± 0.19	0.63 ± 0.20	0.67 ± 0.22	0.19 ± 0.03	0.19 ± 0.02	0.19 ± 0.04	0.20 ± 0.03
3.5 km·hr ⁻¹	0.73 ± 0.20*	0.74 ± 0.22*	0.74 ± 0.21*	0.82 ± 0.24*	0.24 ± 0.04*	0.25 ± 0.05*	0.25 ± 0.04*	0.27 ± 0.04*
4.5 km·hr ⁻¹	0.86 ± 0.26*	0.88 ± 0.26*	0.93 ± 0.24*#	1.10 ± 0.33*#	0.32 ± 0.03*	0.32 ± 0.04*	0.32 ± 0.05*	0.37 ± 0.05*
5.5 km·hr ⁻¹	1.00 ± 0.26*	1.00 ± 0.33*	1.14 ± 0.30*#	1.54 ± 0.36*#	0.44 ± 0.05*	0.44 ± 0.05*	0.46 ± 0.06*	0.53 ± 0.08*

Mean ± SD. $\dot{V}O_2$, net oxygen uptake; VeDBA, vectorial dynamic body acceleration.

* indicates significant difference to 2.5 km·hr⁻¹ within angle ($P < 0.05$)

indicates significant difference to straight walking within speed ($P < 0.05$)

<https://doi.org/10.1371/journal.pone.0182333.t002>

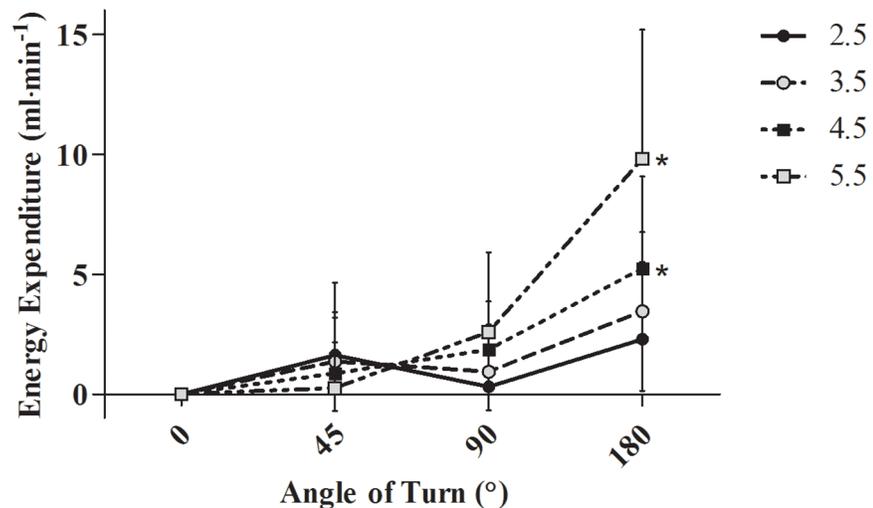


Fig 2. Estimated energetic cost of individual turns at each combination of walking speed and turning angle. * indicates a significant difference in the energy expenditure of turning compared to 45°. Values shown are the difference in energy expenditure between each condition and straight walking.

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The estimated energy expenditure associated with an individual turn is represented in Fig 2, showing the synergistic interaction between speed and turn angle in determining the energy expenditure.

In accord with $\dot{V}O_2$, there was a significant main effect for speed and angle on mean $VeDBA$ during the straights (speed: $F = 1058.734, P < 0.001$; angle: $F = 43.416, P < 0.001$) and corners (speed: $F = 996.671, P < 0.001$; angle: $F = 12.534, P < 0.001$), with a significant interaction effect between speed and angle (straight: $F = 4.497, P < 0.001$; corners: $F = 3.053, P < 0.01$). Specifically, while both straight and corner $VeDBA$ increased with speed, the effect of angle was only manifest at 4.5 and 5.5 $km \cdot hr^{-1}$ (Table 3). For straight sections, $VeDBA$ was dependent on sex ($F = 15.781, P < 0.001$) and peak $\dot{V}O_2$ ($F = 7.437, P < 0.01$) whilst stature was not a significant contributor ($F = 0.038, P > 0.5$). In contrast, corner $VeDBA$ was significantly influenced by sex ($F = 6.723, P < 0.01$) and stature ($F = 4.507, P < 0.05$), but not peak $\dot{V}O_2$ ($F = 0.243, P > 0.05$).

Overall $\dot{V}O_2$ during each condition was significantly correlated with straight ($r^2 = 0.61; P < 0.001$), corner ($r^2 = 0.58; P < 0.001$) and total mean $VeDBA$ ($r^2 = 0.61; P < 0.001$),

Table 3. Mean straight and corner $VeDBA$ during each combination of walking speed and angle.

	Straight Mean $VeDBA$ (g)				Corner Mean $VeDBA$ (g)			
	0°	45°	90°	180°	0°	45°	90°	180°
2.5 $km \cdot hr^{-1}$	0.19 ± 0.03	0.18 ± 0.03	0.19 ± 0.04	0.20 ± 0.03	0.18 ± 0.04	0.18 ± 0.03	0.18 ± 0.04	0.18 ± 0.03
3.5 $km \cdot hr^{-1}$	0.24 ± 0.04*	0.25 ± 0.05*	0.25 ± 0.04*	0.28 ± 0.05*	0.23 ± 0.04*	0.25 ± 0.06*	0.24 ± 0.05*	0.24 ± 0.03*
4.5 $km \cdot hr^{-1}$	0.32 ± 0.04*	0.32 ± 0.04*	0.33 ± 0.04*#	0.39 ± 0.04*#	0.30 ± 0.05*	0.33 ± 0.04*	0.32 ± 0.04*#	0.34 ± 0.05*#
5.5 $km \cdot hr^{-1}$	0.44 ± 0.05*	0.44 ± 0.05*	0.46 ± 0.06*#	0.55 ± 0.09*#	0.42 ± 0.06*	0.44 ± 0.05*	0.45 ± 0.06*#	0.49 ± 0.07*#

Mean ± SD. $VeDBA$, vectorial dynamic body acceleration.

* indicates significant difference to 2.5 $km \cdot hr^{-1}$ within angle ($P < 0.05$)

indicates significant difference to straight walking within speed ($P < 0.05$)

<https://doi.org/10.1371/journal.pone.0182333.t003>

demonstrating a weaker but statistically significant relationship with peak $\dot{V}O_2$ ($r^2 = 0.36$; $P < 0.001$) and stature ($r^2 = 0.32$; $P < 0.001$).

Discussion

This is the first study to investigate the interaction between speed and turn angle in determining the energy expenditure associated with walking. In agreement with one hypothesis, as speed increased for any given turning angle, the associated energy expenditure similarly increased. However, whether angle comprised a significant additional energy expenditure was dependent on the degree of turn angle. Specifically, irrespective of speed, 45° turns did not significantly increase energy expenditure, whilst 180° turns were always associated with a greater energy expenditure than straight line walking. Speed and angle demonstrated a significant interaction; 90° turns were only associated with significantly increased energy expenditure relative to straight line walking at 4.5 and 5.5 km·hr⁻¹. This synergistic interaction was further supported by the exponential relationship found to best represent the relationship between speed and angle [15]. These findings therefore highlight the importance of accounting for the quantity and magnitude of turn completed when estimating energy expenditure, particularly at higher speed and angles.

In recent years there has been increasing recognition of the physiological demands engendered by turning 180° when running. Dellal et al. [31] reported a greater heart rate, blood lactate and ratings of perceived exertion (RPE) during intermittent shuttle runs involving 180° turns compared to straight line running at the same average running velocities, subsequently confirmed by Buchheit et al. [32]. Furthermore, Bekraoui et al. [33] found that covering the same distance at the same average speed resulted in a significantly greater physiological response when the course was 3.5m compared to 7.0m. These earlier findings were recently extended by Hatamoto et al. [17] who found that, even at running speeds as low as 3 km·hr⁻¹, thirty 180° turns per minute elicited a similar metabolic demand as straight line running at 6 km·hr⁻¹. In the present study, a significant increase in total energy expenditure relative to straight line walking was not observed at 2.5 km·hr⁻¹, but was observed at 3.5 km·hr⁻¹. Whilst these findings are largely in accord with those of Hatamoto et al. [17], it is pertinent to note certain methodological discrepancies, such as the training status of the sample population and turning frequencies utilised, which limit inter-study comparisons. Specifically, there were considerable differences in the number of turns completed, with Hatamoto et al. [17] utilising up to 30 turns per minute compared to the 35 turns in 3 minutes at 3.5 km·hr⁻¹ used in the present study.

The greater energy expenditure associated with turning whilst walking is likely to be primarily attributable to the deceleration and subsequent acceleration required to make a turn, both of which necessitate eccentric and concentric muscle contractions, respectively [34]. Acceleration has been shown to engender a greater energy expenditure than travelling at a constant speed, with the energy expenditure dictated by the rate of acceleration [35]. A high acceleration rate requires a high degree of horizontal propulsion [36], therefore the change in acceleration is greater when performing a 180° turn at higher running velocities, thereby resulting in greater energy expenditure.

The extent of the angle turned has also been shown to alter the biomechanical properties in running; a 90° turn exerts a significantly higher vertical, braking and propelling force than a 45° turn [37]. It would therefore be postulated that greater angles would also be associated with further increases in directional forces and thus energy expenditure during walking. In accord with this hypothesis, a linear relationship has been suggested between angle and energy expenditure when walking at 6 km·hr⁻¹ [18]. However, the present study suggests a synergistic

interaction between speed and angle, with the influence of increasing angle within a speed only evident at $4.5 \text{ km}\cdot\text{hr}^{-1}$ and above. This discrepancy may be attributable to differences in the walking velocities, the specific techniques used to turn, stature or training status [32, 38]. Indeed, both stature and peak $\dot{V}\text{O}_2$, an indicator of aerobic fitness and training status, were significant predictors of energy expenditure in the present study. Hatamoto et al. [16] previously suggested that ball game players, who are likely to be mainly running rather than walking and who turn more frequently anyway, were likely to have a more efficient turning technique. However, the mean $\dot{V}\text{O}_2$ of an individual turn was reported to be $0.34 \pm 0.13 \text{ ml}\cdot\text{kg}^{-1}$ and $0.55 \pm 0.09 \text{ ml}\cdot\text{kg}^{-1}$ at $4.3 \text{ km}\cdot\text{hr}^{-1}$ and $5.4 \text{ km}\cdot\text{hr}^{-1}$, respectively [16]. These values are substantially more than the values observed in the present study (Fig 2: $4.5 \text{ km}\cdot\text{hr}^{-1} = 0.07 \pm 0.03 \text{ ml}\cdot\text{kg}^{-1}$; $5.5 \text{ km}\cdot\text{hr}^{-1} = 0.13 \pm 0.07 \text{ ml}\cdot\text{kg}^{-1}$), despite the less trained status of the present participants. The reason for this discrepancy and its contradiction to the postulated role of aerobic fitness and technique are presently unclear, although it is perhaps pertinent to note the different methods of calculating the energy expenditure of an individual turn and the recent findings of Zagatto et al. [39] who found a lower metabolic power to be associated with more frequent changes of direction.

It is interesting to note the apparent dissociation between $VeDBA$ and turning angle in the present study, whereby increasing the angle of the turn was not associated with any significant increase in $VeDBA$. This could be attributable to the short duration of the turns, although the high measurement resolution makes this unlikely, or measurement error associated with the use of magnetometry to isolate the turn. However, whilst the magnitude of change in the signal was decreased at lower turn angles, this is unlikely to entirely explain the present findings. Rather, this finding may largely be attributable to the complex and individual-specific interaction between the surge, heave and sway components of DBA as well as muscular effort that involves generation of high forces without the dynamism typical of straight-line travel. Indeed, recent studies using force plates to investigate turn kinetics suggest that during a turn, the surge (inline) component of DBA is accompanied by a sway (perpendicular) component (Griffiths et al., In press). Furthermore, the surge component tends to 'average' zero over the straight sections (equal deceleration and acceleration phases) but during a turn section, the surge component becomes negative on average to provide the deceleration required to enter and execute the turn. In addition, the heave component (vertical) component of DBA may increase above and beyond normative walking values but this may depend on the turning technique being employed, e.g. some participants may elect to turn using a 'stop and reverse direction' method while others may prefer a 'gradual cornering' approach. The authors are of the opinion that this is by far the most likely explanation for the lack of sensitivity of $VeDBA$ to turns.

The present findings have significant implications within both sporting and health contexts given that few sporting, fitness or functional activities occur in a strictly linear fashion [37]. Indeed, whilst the present study only considered walking and caution should be exercised when extrapolating the findings to speeds associated with running and team sports, it is perhaps pertinent to note the similarity between the current findings and those reported elsewhere. Specifically, Dellal et al. [31] reported a greater heart rate, blood lactate and ratings of perceived exertion (RPE) during intermittent shuttle runs involving 180° turns compared to straight line running at the same average running velocities, subsequently confirmed by Buchheit et al. [32]. Furthermore, Bekraoui et al. [33] found that covering the same distance at the same average speed resulted in a significantly greater physiological response when the course was 3.5m compared to 7.0m. These earlier findings were recently extended by Hatamoto et al. [17] who found that, even at running speeds as low as $3 \text{ km}\cdot\text{hr}^{-1}$, thirty 180° turns per minute

elicited a similar metabolic demand as straight line running at $6 \text{ km}\cdot\text{hr}^{-1}$. In the present study, a significant increase in total energy expenditure relative to straight line walking was not observed at $2.5 \text{ km}\cdot\text{hr}^{-1}$, but was observed at $3.5 \text{ km}\cdot\text{hr}^{-1}$. Whilst these findings are largely in accord with those of Hatamoto et al. [17], certain methodological differences should be considered, such as the training status of the sample population and turning frequencies utilised, which limit inter-study comparisons. Specifically, there were considerable differences in the number of turns completed, with Hatamoto et al. [17] utilising up to 30 turns per minute compared to the 35 turns in 3 minutes at $3.5 \text{ km}\cdot\text{hr}^{-1}$ used in the present study. However, not all studies have found a significant influence of turning on energy expenditure, with Zamparo et al. [40] reporting no change in $\dot{V}\text{O}_2$ with increasing turn angle from 0 to 180° . This discrepancy may be related to the use of maximal running velocity during this study, thereby minimising the potential for further increases in $\dot{V}\text{O}_2$ to be elicited with increasing turn angle. Nonetheless, we would concur with Hatamoto et al. [16] that the energy expenditure associated with turning should be considered when estimating total energy expenditure during a football game in which more than 700 turns are typically completed per match [19].

From a health perspective, one important application of the present findings is in the design and interpretation of physical activity interventions. For example, the majority of energy expenditure prediction algorithms based on accelerometry data are derived from treadmill exercise. Such linear modes of locomotion are not cognisant of the additional metabolic costs associated with turning and this may, to some extent, contribute to the poor accuracy associated with the derived models during free-living conditions [41, 42]. Such inaccuracies are likely to be emphasised in certain populations, such as children, who are characterised by highly sporadic movements [43, 44]. Furthermore, accounting for the energy expenditure of turning could also be important in the evaluation of clinical trial effectiveness. Whilst the six-minute walking test is designed to be conducted over a 30m, straight line course with a 180° turn [20], reported distances covered range from 20 to 50 m [21, 22] due to space and resource limitations. Such discrepancies, using reference values reported by Chetta et al. [45] could result in the number of turns ranging from 12 to 32, which, according to the present data, may be associated with an additional $\dot{V}\text{O}_2$ expenditure ranging from $118 \text{ ml}\cdot\text{min}^{-1}$ to $296 \text{ ml}\cdot\text{min}^{-1}$. Swank et al. [46] demonstrated that a 6% improvement in peak $\dot{V}\text{O}_2$ was associated with a 5% decrease in risk of all-cause mortality in Congestive Heart Failure patients. Given the significantly lower peak aerobic capacity in patients, discrepancies arisen from failing to account for the energy expenditure of turning, which could be as much as 20% of a patients peak $\dot{V}\text{O}_2$, would considerably alter the interpretation of intervention efficacy. Future studies should seek to generate algorithms that account for distance and turns completed during a six-minute walk test, facilitating standardisation between centres.

There are certain limitations associated with the current study that should be acknowledged, such as the walking velocities utilised. Previous studies have employed higher running speeds, whereas we employed speeds more typical of habitual physical activity. Whilst this increased the generalisability of our findings to health contexts, caution should be taken when extrapolating these findings to a sporting context. Furthermore, although a strength of the study to optimise interpretation of our results, the controlled nature of the protocol limits ecological validity. Finally, although the walking speeds were associated with a moderate intensity of exercise for most of the participants, some may not have achieved a steady state $\dot{V}\text{O}_2$ within the 3-minute bout, thereby influencing the mean $\dot{V}\text{O}_2$ observed.

In conclusion, the present study demonstrated a synergistic interaction between speed and angle in determining the energy expenditure associated with walking. Specifically, 90° and 180° turns are associated with significant additional metabolic costs at $4.5 \text{ km}\cdot\text{hr}^{-1}$ and above.

These findings therefore highlight the importance of accounting for the quantity and magnitude of turns completed when estimating energy expenditure and have significant implications within both sport and health contexts.

Supporting information

S1 File. Minimum required dataset.
(XLSX)

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