

A novel method for calculating the energy cost of turning during running

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Abstract: Although changes of direction are one of the essential locomotor patterns in ball sports, the physiological demand of turning during running has not been previously investigated. We proposed a novel approach by which to evaluate the physiological demand of turning. The purposes of this study were to establish a method of measuring the energy expenditure (EE) of a 180° turn during running and to investigate the effect of two different running speeds on the EE of a 180° turn. Eleven young, male participants performed measurement sessions at two different running speeds (4.3 and 5.4 km/hour). Each measurement session consisted of five trials, and each trial had a different frequency of turns. At both running speeds, as the turn frequency increased the gross oxygen consumption ($V \cdot O_2$) also increased linearly (4.3 km/hour, $r = 0.973$; 5.4 km/hour, $r = 0.996$). The $V \cdot O_2$ of a turn at 5.4 km/hour (0.55 [SD 0.09] mL/kg) was higher than at 4.3 km/hour (0.34 [SD 0.13] mL/kg) ($P < 0.001$). We conclude that the gross $V \cdot O_2$ of running at a fixed speed with turns is proportional to turn frequency and that the EE of a turn is different at different running speeds. The Different Frequency Accumulation Method is a useful tool for assessing the physiological demands of complex locomotor activity.

Keywords: energy expenditure, turning, turn frequency, running speed, $V \cdot O_2$, heart rate

Introduction

In ball games such as handball, basketball, rugby, and soccer, players frequently accelerate and decelerate to change direction, for example, in order to evade or overtake opponents. Most soccer players in the English Premier League make more than 700 turns per match.¹ Turning while running requires modification of the locomotor pattern to direct the momentum of straight running in a new direction by applying an additional impulse to the ground. Because of the deceleration and acceleration of the center of mass that occurs with directional change, turns may impose more physiological demands on athletes than straight running. Although several previous studies have reported the biomechanical^{2,3} and/or medical^{4,5} aspects of turning during sports, studies of the physiological demand imposed on athletes by turning are limited. Some studies have examined the aerobic physiological demands of walking or running by analysis of expired gas;^{6,7} however, the energy expenditure (EE) required to perform a turn while running is currently unknown because it is difficult to evaluate. The objective of our study was to separate the EE of a turn from the EE of straight running by using the Different Frequency Accumulation Method, a novel approach combining the accumulation method with changing of turn frequency, to evaluate the instantaneous physiological demands of turning during running.

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Various graded tests have been conducted to estimate energy consumption during running; however, combining these tests with turning is an innovative approach. We hypothesized that if a person runs the same distance at a constant average speed, the gross EE will increase when turning while running compared to the EE of straight running. Gross EE can be expressed as the sum of the EE of turns plus the EE of straight running.

By using the Different Frequency Accumulation Method in this study, we established a method for the measurement of the EE of a 180° turn during straight line running and examined whether the EE of a 180° turn changes with different running speeds.

Methods

Ten recreationally active male volunteers participated in this study and the following information determined: mean age (22.8 [standard deviation (SD) 2.0] years), height (1.72 [SD 0.05] m), body mass (63.1 [SD 5.6] kg), and peak gross oxygen consumption (peak $V \cdot O_2$) (48.4 [SD 4.4] mL/kg/minute). Aerobic capacity was measured using the incremental exercise test (peak $V \cdot O_2$) on a bicycle ergometer. Eight of the participants were experienced soccer players, and the remaining two had played rugby or volleyball regularly for more than 6 years. All were free of any injury that might influence their athletic performance.

This study was approved by the Ethical Committee of Fukuoka University, Fukuoka, Japan (number 10-02-02), and informed consent was obtained from all participants. This study followed the World Medical Association Declaration of Helsinki; Ethical Principles for Medical Research Involving Human Subjects; and Ethical Guidelines for Epidemiological Research by the Ministry of Education, Culture, Sports, Science, and Technology and the Ministry of Health, Labor, and Welfare, Japan.

All participants completed one familiarization session and two measurement sessions. We conducted the experiments in an indoor facility with flooring, and the participants were instructed to wear the same indoor sports shoes for all trials. On the day of the familiarization session, the participants were given instructions on performing the required turns while running using the sidestep cutting technique.^{2,3,8} The sidestep cutting technique involves the outgoing path proceeding away from the support leg side. Participants performed a turn for both legs, with an equal number of times for both the left and right legs. These movements were then practiced until the participants could consistently

repeat the movement for the required time. All participants were instructed to avoid food, caffeine, tobacco products, and alcohol for 3 hours prior to the sessions.

Each measurement session consisted of five running trials of 5 minutes each at a fixed speed, with different running distances necessitating different turn frequencies. Running speeds for the two measurement sessions were 4.3 km/hour and 5.4 km/hour. Running distances for each trial were 3, 3.6, 4.5, 6, and 9 m (Figure 1), with the participants performing a 180° turn after covering the required distance and repeating this for the full 5-minute period. The frequency of the turns for each running distance was 24, 20, 16, 12, and 8 times/minute at 4.3 km/hour and 30, 25, 20, 15, and 10 times/minute at 5.4 km/hour. Running speeds were controlled using a metronome (DM-17 Seiko Digital Metronome; Seiko Corporation, Tokyo, Japan) that measured 2.00 seconds (60 beats per minute [bpm], 1 beat = 1 second) for a speed of 5.4 km/hour and 2.50 seconds (50 bpm, 1 beat = 1.25 seconds) for 4.3 km/hour for a distance of 3.0 m. The metronome speed was adjusted for each particular case (3.6 m, 2.40 seconds [50 bpm] and 3.00 seconds [60 bpm]; 4.5 m, 3.00 seconds [60 bpm] and 3.75 seconds [48 bpm]; 6.0 m, 4.00 seconds and 5.00 seconds [both 60 bpm]; 9.0 m, 6.00 seconds [60 bpm] and 7.50 seconds [48 bpm], for 5.4 km/hour and 4.3 km/hour, respectively). As long as they kept the pace indicated by

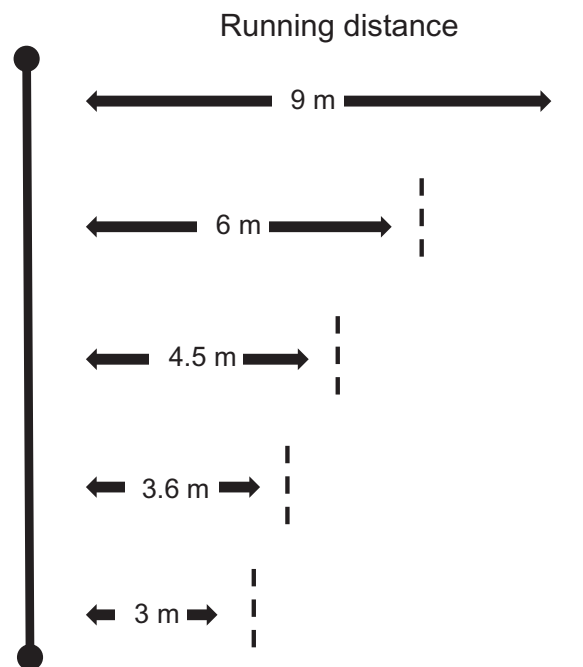


Figure 1 Course outline showing the running distances for each set. **Note:** Participants ran back and forth between two lines at running speeds of 4.3 and 5.4 km/hour.

the metronome, the participants were allowed to use their own preferred stride frequency as it has been shown that this results in the lowest oxygen consumption ($V \cdot O_2$).^{9,10} The order in which participants performed the trials was randomly determined, and participants rested at least 15 minutes between each trial.

We calculated the EE of a turn from the slope of the regression line for EE against turn frequency (Figure 2). The EE of a turn included the linear deceleration to slow down the forward velocity as the runner initiated the change in heading direction and the linear acceleration to get the runner back up to the target running speed after the body had been rotated. If the EE of one turn while running at a constant average speed is expressed by the coefficient α , gross EE may be calculated using a linear regression model as follows:

$$\text{Gross EE (kJ/minute)} = \alpha \text{ (kJ)} \times f \text{ (turn/minute)} + \text{Running EE (kJ/minute)},$$

where Gross EE is the gross energy expenditure, α is the EE of a 180° turn, f is the turn frequency, and running EE is the EE at constant velocity (Figure 1). The coefficient α might differ at different running speeds because kinetic momentum and physical load increase with greater running velocity.

Heart rate (HR) was measured for the last minute of each 5-minute trial (representing a steady-state condition during exercise) with a Polar HR monitor (CE0537; Polar Electro, Kempele, Finland). After completing each trial, participants were asked to rate their perceived exertion (RPE) using the Borg Scale.¹¹

We investigated the EE of a turn during running using the Different Frequency Accumulation Method. The EE during each running trial was measured by collecting an expired gas

sample through a facemask. Respiratory gas analysis was conducted using the mixing chamber method^{12,13} to evaluate the volume of expired air, and the O_2 and CO_2 fractions were analyzed by mass spectrometry (ARCO 2000; ARCO System, Chiba, Japan) every 12 seconds and averaged to 1 minute. At the beginning of each trial the metabolic system was calibrated using a 3-L calibration syringe for volume calibration and two different gas mixtures of known concentrations (20.93% O_2 and 0.04% CO_2 ; 15.00% O_2 and 4.55% CO_2) for calibration of the gas analyzers. Oxygen consumption ($V \cdot O_2$) was assessed for the final 2 minutes of each running trial, and the average $V \cdot O_2$ (mL/kg/minute) over those 2 minutes was calculated. The EE (kJ) was estimated from respiratory exchange data using the equation of Lusk.¹⁴

Results are given as the mean (SD). Linear regression analyses were applied to calculate slopes and intercepts and 95% confidence intervals (CI) were calculated. Two-way analysis of variance was used to compare the slope of the $V \cdot O_2$ of a turn, HR, and RPE obtained at the two different running speeds (4.3 and 5.4 km/hour \times turn frequencies). Differences were considered significant at an α level of $P < 0.05$. All statistics were conducted by SPSS software (v20; IBM Corporation, Armonk, NY, USA).

Results

All participants successfully completed both measurement sessions. At both running speeds, as the turn frequency increased the $V \cdot O_2$, HR, and RPE of turning also increased (Figure 3). There was a significant correlation between $V \cdot O_2$ and turn frequency (mean $r = 0.973$ and $r = 0.996$ at 4.3 km/hour and 5.4 km/hour, respectively). The mean $V \cdot O_2$ mL/kg of a turning was ~ 0.34 (SD 0.13, 95% CI: 0.193–0.492) at 4.3 km/hour, and 0.55 (0.09, 95% CI: 0.467–0.641) at a 5.4 km/hour running speed. The difference in the mean $V \cdot O_2$ of a turn between the 4.3 and 5.4 km/hour running speeds was statistically significant ($P < 0.001$). The slopes of the regression equations of HR versus turn frequency at each running speed were significantly different ($P < 0.001$), but the slopes of the regression equations of RPE versus turn frequency did not significantly differ at different running speeds ($P = 0.390$). The physiological demand of a single turn was 7.2 (SD 2.9) and 12.0 (SD 2.1) J/kg at 4.3 and 5.4 km/hour, respectively.

Discussion

The objectives of this study were to establish a technique for the measurement of the EE of a 180° turn during running and to investigate the effect of different running speeds on the EE of

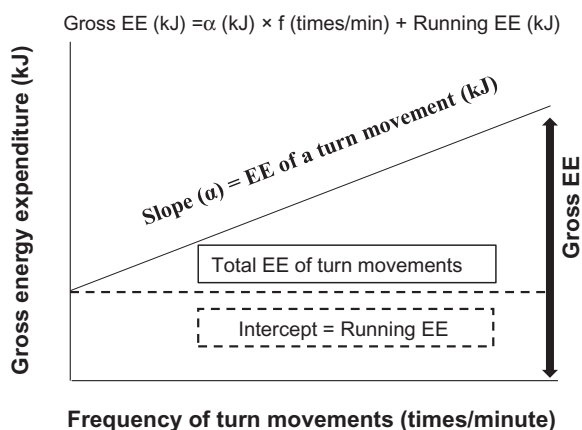


Figure 2 Relationship between gross EE and turn frequency.
Abbreviations: EE, energy expenditure; α , EE of a 180° turn at one running speed; f , turn frequency; running EE, the EE at constant velocity.

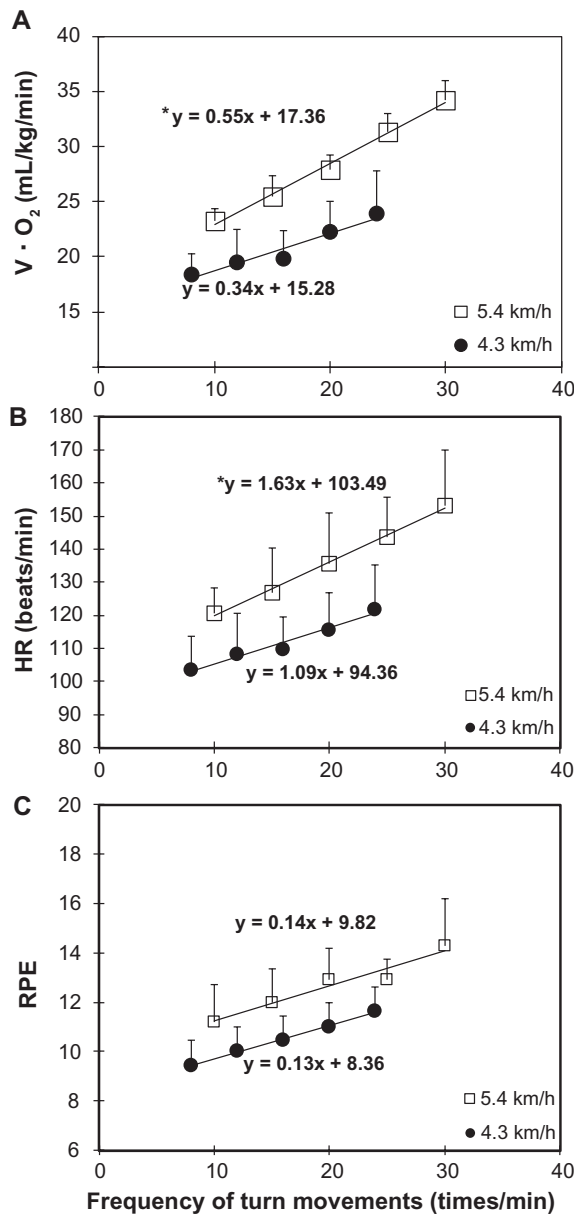


Figure 3 Relationship between turn frequency and oxygen consumption (A), heart rate (B), and RPE (C), while running at different speeds.

Notes: The slopes of the regression equations for $V \cdot O_2$ versus turn frequency and HR versus turn frequency were significantly different at running speeds of 4.4 and 5.4 km/hour ($*P < 0.001$). The slopes of the regression equations for RPE versus turn frequency did not differ significantly at different speeds ($P = 0.390$).

Abbreviations: HR, heart rate; RPE, rated perceived exertion; $V \cdot O_2$, gross oxygen consumption.

a 180° turn. The results of this study indicate that gross $V \cdot O_2$ increased linearly as turn frequency increased. In addition, the $V \cdot O_2$ of a turn was significantly higher at a higher running speed (Figure 3).

The results of this study show that the EE of turning during running can be calculated using the Different Frequency Accumulation Method. As this is the first study to quantify the physiological demands of turning during running, we

cannot directly compare our results with those of other studies. However, some previous studies have addressed related topics. Preplanned cutting tasks during running have been shown to increase biomechanical load when compared with straight running.^{2,4,5} A 90° change in direction while running showed a significantly larger vertical, braking, and propelling force compared to a 45° change in direction. A sharper angle of turning would require a higher EE. Turning while running requires deceleration and acceleration movements and muscle work in eccentric and concentric muscular contraction.¹⁵ Eccentric muscle effort associated with deceleration would increase energy cost. The estimated energy cost in the acceleration phase of running is higher than the energy cost while running at a constant speed.¹⁶ The results of these studies suggest that a greater EE would occur during turning than during straight running. In addition, Dellal et al¹⁷ compared physiological responses of classical in-line intermittent exercise (running straight forward) with those of a specific intermittent shuttle exercise with 180° directional changes at the same average running speeds. They reported that HR, blood lactate, and RPE were significantly higher in the intermittent shuttle exercise that included 180° turns than in in-line running and concluded that shuttle exercise increased physiological responses possibly because turning needs additional muscular action to that required in deceleration and acceleration. Our results demonstrate that $V \cdot O_2$, HR, and RPE increase linearly as turn frequency increases; this confirms that turning during running generates higher physiological demands than straight running.

Our results show that the EE required for a 180° turn at 5.4 km/hour is significantly higher than the EE required for a turn while running at 4.3 km/hour ($P < 0.001$). The 180° turn has both an acceleration and deceleration phase, and the EE in the acceleration phase during running depends on the acceleration rate.¹⁶ As a high magnitude of horizontal propulsion is required to achieve high acceleration rates,¹⁸ the acceleration change is greater when performing a 180° turn at higher running speeds. Therefore, turns at faster running speeds demand more EE. This is supported by our finding that HR increased more with increased turning frequency at running speeds of 5.4 km/hour than at 4.3 km/hour ($P < 0.001$), indicating that the physiological demand of turning is greater at the higher running speed. However, there was no statistically significant difference in the relationship between RPE and turn frequency at different running speeds ($P = 0.390$). This may be due to the relatively low running speeds that we used in this study, which might not impose heavy physiological loads that would be perceived as significantly increased exertion

by the athletic participants. The relationship between the psychological and physiological demands of turning at various running speeds needs further investigation.

The 180° turn technique is likely to be more efficient in ball game players who turn frequently than in those who do not. The value of $V \cdot O_2$ max using a shuttle run test in long-distance runners was underestimated compared with values obtained using a treadmill protocol.¹⁹ The shuttle run test includes repeated turning movements, and these movements were unfamiliar for long-distance runners. It is likely that the turn technique could result in differences in EE of a turn. Nine soccer players and one volleyball player were the subjects in this study. Although football players perform turns more frequently compared with volleyball players, the EE of a turn was not significantly different. The reason for this may be the running speed of the subjects. The difference in the EE of turning would likely be more evident when running speed is increased. For ball game players who turn frequently, turn efficiency may be important to save energy and to help improve performance during a game.

We hypothesized that the intercept of the regression line of $V \cdot O_2$ versus turn frequency can be considered the $V \cdot O_2$ at a constant running speed without turning on a flat road. Although we did not measure the $V \cdot O_2$ of running on a flat road without turning, the $V \cdot O_2$ predicted in the present study is comparable to previously reported values of $V \cdot O_2$ during running. The American College of Sports Medicine (ACSM) guidelines provide formulas to estimate $V \cdot O_2$ for walking and running speeds on a treadmill.²⁰ We compared our results with the $V \cdot O_2$ values obtained using these formulas because most exercise physiologists are familiar with the ACSM guidelines. We also compared the intercept value of our equation with Leger's equation.²¹ Hall et al²² compared the actual EE for running with some of the published prediction equations for EE during running and reported that Leger's prediction equation model is the most accurate in young healthy populations, although the equation just slightly overestimates the actual EE. The $V \cdot O_2$ values predicted using the intercept of the $V \cdot O_2$ versus turn frequency regression line in the present study were 15.3 (1.7) and 17.4 (1.6) mL/minute/kg (4.3 and 5.4 km/hour, respectively). The $V \cdot O_2$ values predicted by the ACSM formula were 17.9 and 21.5 mL/kg/minute, which are higher than our data. The $V \cdot O_2$ of treadmill running has been reported as being higher than that of track running.²³ Ruiz and Sherman reported that the ACSM metabolic equation significantly overestimated the oxygen cost of running.²⁴ The $V \cdot O_2$ estimated by Leger's equation was 15.8 and 19.3 mL/minute/kg for running speeds of 4.3 and 5.4 km/hour, respectively, which was slightly higher

than our data but consistent with Hall's report.²² These are small differences, and the Different Frequency Accumulation Method seems to be a reasonable approach to evaluate the physiological demand of turning during running.

Previous studies have indicated that the EE calculated from distance covered and running speeds in a traditional video analysis system using published equations were underestimated when compared with the EE calculated using direct measurements of $V \cdot O_2$ in ball games, such as soccer (estimated EE 653 to 884 kcal²⁵ vs actual EE 1140 and 1195 kcal^{26,27}). This estimated value failed to account for the additional metabolic demands of turning, stopping, jumping, and tackling.^{27,28} We propose adding the value of EE for turning to the value of EE estimated for the running distance when calculating the total EE in a soccer match. English Premier League soccer players perform more than 700 turns per game.¹ We estimated the value of EE from only the number of turns per match as about 140 kcal; however, this value is insufficient if soccer players made 700 turns with 180° turns while running at 5.4 km/hour during a match. In recent years as technology has advanced, the development of tools, such as global positioning systems and multivideo analysis systems, has made it possible to track field players more easily and accurately.^{29,30} The results of our present study may be helpful for evaluating the physiological demand and estimating the EE of players more accurately using video analysis or GPS.

The limitation of this study was that the participants ran at only two low running speeds. During a match, soccer players run at speeds ranging from 0 to more than 25 km/hour.^{25,29} Therefore, investigation of the physiological demands of turning at additional running speeds is necessary to confirm that our method is applicable in a match situation. In addition, because turns are made at variable angles during a soccer match,¹ examining the influence of the turn angle (0° to 180°) on physiological demands is also necessary. Once the relationship between the energy cost of turning, the running speed, and the turn angle are clarified, expanding the application of our Different Frequency Accumulation Method to the actual match situation will be practical.

Conclusion

As turn frequency increased while a constant average speed was maintained, the gross EE increased linearly. This indicates that a certain amount of EE is required when a turn is made at a set speed and that the physiological demands of complex locomotor activities, such as turning, can be quantified using our Different Frequency Accumulation Method. Our results also indicate that as the running speed increased, the EE required for a turn

also increased. The physiological demand of a single turn was 7.2 J/kg at 4.3 km/hour and 12.0 J/kg at 5.4 km/hour. This is the first study to quantify the physiological demands of turning while running. This information may be helpful for estimating the EE of players in a match when using video analysis and for designing training programs that include turns.

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Disclosure

The authors report no conflicts of interest in this work.

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