博士学位論文

The physiological demands of change of direction while running.

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Contents

Abstract

In ball sports such as basketball and rugby, it is of high importance to objectively evaluate individuals and the team as well as perform strategy analysis.

The first research analyzing movements of soccer players during the game was conducted more than 40 years ago. Nowadays, a modern tracking method allows tracking soccer players through video camera and calculating the exact movement distance using location information. Another study describes calculations of estimated energy expenditure (EE) based on exact distance data (da Silva et al, 2008; Seliger,1968). Correct dietary intake and nutrition balance is of crucial importance for the players' performance so disclosing the details of EE during the game is highly significant. However soccer requires various kinds of motions other than straight running alone, thus it is possible that such calculations underestimate the real EE value.

It is known that the most frequently performed motion is change of direction (COD): 750 to 1000 CODs per game (Bloomfield et al, 2007). Calculating EE

of CODs would permit to calculate the total EE of players during the game with a lower risk of underestimation. However, the energy cost of COD has not been studied so far. It is difficult to evaluate the energy expenditure of tuning because turn is spontaneous movement. So, our first study was to establish the method in order to measure the COD while running. Secondly, we examined the effect of running speeds on physiological demands of COD.

Chapter 1

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

Keywords Energy expenditure・turn movement ・turn frequency・running speed

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. Thus, we proposed a novel method, termed the "Different Frequency Accumulation Method," to evaluate the physiological demand of turning. The purposes of this study were: 1) to establish a method of measuring the energy expenditure (EE) of a 180° turn during running, and 2) 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/h). Each measurement session consisted of five trials, and each trial had a different frequency of turns. At both running speed, as the turn frequency increased the gross oxygen consumption (VO_2) also increased linearly (4.3 km/h, $r = 0.973$; 5.4 km/h, $r = 0.996$). The VO_2 of a turn at 5.4 km/h (0.55 (0.09) ml/kg) was higher than at 4.3 km/h (0.34 (0.13) ml/kg)($P < 0.001$). Thus, we conclude that the gross VO_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, VO_2, heart rate.

1. 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. Thus, because of the deceleration and acceleration of the center of mass that occurs with direction 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. A large number of 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 the experiments described here was to separate the EE of a turn from the EE of straight running using the "Different Frequency Accumulation Method," a novel approach for evaluating the instantaneous physiological demands of turning during running.

The Different Frequency Accumulation Method used in this study is a method to estimate the energy consumption of turning during running. Various graded tests have been conducted so far, but combining them 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 be increased in case of turning while running as compared with the EE of straight running. Gross EE can be expressed as the sum of the EE of turns plus the EE of straight running.

The purposes of this study were: 1) to establish a method for the measurement of the EE of a 180° turn during straight line running, and 2) to examine whether the EE of a 180° turn changes with different running speeds using the “Different Frequency Accumulation Method.”

2. Methods

Ten recreationally active male volunteers participated in this study. The mean age, height, body mass and peak VO_2 max (aerobic capacity was measured using the incremental exercise test (peak VO_2) on a bicycle ergometer) of participants were 22.8 (2.0) y, 1.72 (0.05) m, 63.1 (5.6) kg and 48.4 (4.4) ml/kg/min, respectively. 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 WMA Declaration of Helsinki, Ethical Principles for Medical Research Involving Human Subjects, and Ethical Guidelines for Epidemiological Research by Ministry of Education, Culture, Sports, Science and Technology and Ministry of Health, Labour 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 instructed in how to perform 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. A turn was performed for both legs, 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 3hr prior to the sessions.

Each measurement session consisted of five running trials of five 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/h and 5.4 km/h. 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 five minute period. The frequency of the turns for each running distance was 24, 20, 16, 12 and 8 times/min at 4.3 km/h and 30, 25, 20, 15 and 10 times/min at 5.4 km/h, respectively. Running speeds were controlled using a metronome (DM-17, Seiko Digital Metronome, Seiko Corp, Tokyo, Japan) that measured 2 seconds (60 beats per minute: bpm, 1 beat is 1 second) for the speed of 5.4 km/h and 2.50 seconds (50 bpm: 1 beat is 1.25 seconds) for 4.3 km/h for the distance of 3.0 m, and was adjusted similarly for each particular case (3.6 m: 2.40 s (50 bpm) and 3.00 s (60 bpm), 4.5 m: 3.00 s (60 bpm) and 3.75 s (48 bpm), 6.0 m: 4.00 s and 5.00 s (both 60 bpm), 9.0 m: 6.00 s (60 bpm) and 7.50 s (48 bpm) for 5.4 km/h and 4.3 m/h, respectively). As long as they kept the pace indicated by 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 (VO_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 regression 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:

Gross EE (kJ/min) = α (kJ) * f (turn/min) + running EE (kJ/min) (1)

where Gross EE is the gross energy expenditure, α is the EE of a 180 degree 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 was measured for the last minute of each five-minute trial (representing a steady-state condition during exercise) with a Polar heart rate 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 turning 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 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 one 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 (VO_2) was assessed for the final two minutes of each running trial and the average VO_2 (ml/kg/min) over those two minutes was calculated. The EE (kJ) was estimated from respiratory exchange data using the quation of Lusk. [12]

Statistics. The results are given as the mean (SD). Linear regression analyses were applied to calculate slopes and intercepts and 95 percent confidence intervals were calculated. Two-way ANOVAs were used to compare the slope of the VO_2 of a turn, HR and RPE obtained at the two different running speeds (4.3 and 5.4 km/h × turn frequencies). Differences were considered significant at an alpha level of $P < 0.05$. All statistics were conducted by SPSS software (SPSS, version 20, SPSS, Chicago, IL, USA).

3. Results

All participants successfully completed both measurement sessions. At both running speeds, as the turn frequency increased the VO_2, HR and RPE of turning also increased (Figure 3). There was a significant correlation between VO_2 and turn frequency (mean $r = 0.973$ and $r = 0.996$ at 4.3 km/h and 5.4 km/h, respectively). The mean VO_2 ml/kg of a turning was 0.34 (0.13; 95 percent confidence interval, 0.193 to 0.492) at 4.3 km/h and 0.55 (0.09; 95 percent confidence interval, 0.467 to 0.641) at a 5.4 km/h running speed. The difference in the mean VO_2 of a turn between the 4.3 and 5.4 km/h 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 (2.9) and 12.0 (2.1) J/kg at 4.3 and 5.4 km/h, respectively.

4. Discussion

The objectives of this study were: 1) to establish a technique for the measurement of the EE of a 180° turn during running, and 2) to investigate the effect of different running speeds on the EE of a 180° turn. The results of this study indicate that gross VO_2 increased linearly as turn frequency increased. In addition, the VO_2 of a turn was significantly higher at the 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 compare the results of present study directly with those of other studies. However, some previous studies have looked at related topics. Pre-planned cutting tasks during running have been shown to increase biomechanical load when compared with straight running.[2,4,5] The 90° change of direction while running significantly showed the larger vertical, braking and propelling force than 45° change of direction. A shaper angle of turning would require higher EE. Turning while running requires deceleration and acceleration movements and muscle work in eccentric and concentric muscular contraction.[13] 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.[14] The results of these studies suggest that greater EE would occur during turning than during straight running. In addition, Dellal et al,[15] 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 including

180° turns than in in-line running, and stated that shuttle exercise increased physiological responses possibly because the turning needs additional muscular action required in deceleration and acceleration. Current study results demonstrate that the VO_2, HR and RPE increase linearly as turn frequency increases; this confirms that turning during running generates higher physiological demands than straight running.

The present results show that the EE required for a 180° turn at 5.4 km/h is significantly higher than the EE required for a turn while running at 4.3 km/h ($P < 0.001$). The 180° turn has both an acceleration and deceleration phase, and the EE in the acceleration phase during running depends on the acceleration rate itself.[14] As a high magnitude of horizontal propulsion is required to achieve high acceleration rates,[16] the amount of 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/h than at 4.3 km/h ($P < 0.001$), indicating that the physiological demand of turning is greater at the higher running speed. However, there was no statically 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 use turning frequently than in those who do not. The value of VO_2 max using a shuttle run test in long distance runners was underestimated compared with values obtained using a treadmill protocol. The shuttle run test includes repeated turning movements and these movements were unfamiliar for long-distance runners. It is likely that turn technique could result in differences in EE of a turn. Nine football players and one volley ball player were the subjects in this study. Although football players perform turns more frequently compared with volleyball players, EE of a turn was not significantly different. The reason for this may be the running speed of the subjects. The difference in EE of turning would likely be more evident when running speed is increased. For ball game players who perform a lot of turning, turn efficiency may be very important to save energy and help improve performance during a game.

We hypothesized that the intercept of the regression line of VO_2 versus turn frequency can be considered the VO_2 at a constant running speed without turning on the flat road. Although the present study did not measure the VO_2 of running on the flat road without turning, the VO_2 predicted in the present study is comparable to previously reported values of VO_2 during running. The American College of Sports Medicine (ACSM) guidelines provides formulas to estimate VO_2 for walking and running speeds on a treadmill. [18] We compared the results of the present study with the VO_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.[19] Hall et al,[20] 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. Thus, the values of VO_2 of the intercept from the results of present study were compared with the value of previous equation. The VO_2 values predicted using the intercept of the VO_2 versus turn frequency regression line in the present study were 15.3 (1.7) and 17.4 (1.6) ml/min/kg (4.3 and 5.4 km/h, respectively). The VO_2 values predicted by the ACSM formula were 17.9 and 21.5 ml/kg/min, which are higher than our data by 2.6 and 4.1 ml/kg/min (for 4.3 and 5.4 km/h running speed, respectively). Meyer et al,[21] reported that the VO_2 of treadmill running was higher than that of track running. Ruiz and Sherman[22] also reported that the ACSM metabolic equation significantly overestimated the oxygen cost of running. The VO_2 estimated by Leger's equation was 15.8 and 19.3 ml/min/kg, for running speeds of 4.3 and 5.4 km/h, respectively. Leger's equation yielded slightly higher estimates than our data by 0.5 and 1.9 ml/kg/min, which is consistent with the Hall's report[20]; these are small difference. On the basis of these results, our "Different Frequency Accumulation Method" seems a reasonable approach to evaluate the physiological demand of turning during running.

Previous studies indicate 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 VO_2 in ball games, such as soccer (Estimated EE : 653 to 884 kcal [23] vs Actual EE : 1140 and 1195 kcal [24,25]). This estimated value failed to account for the additional metabolic demands of turning, stopping, jumping and tackling.[25,26] 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 performed 700 turns with 180° turns while running at 5.4 km/h during a match. In recent years, as technology has advanced, the development of tools such as global positioning systems (GPS) and multi-video analysis systems has made it possible to track field players more easily and accurately.[27,28] 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 systems.

The limitation of the 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/h.[23,27] 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 its physiological demands is also necessary. Once the relationship between the energy cost of turning, the running speed, and the turn angle become clear, expanding the application of our "Different Frequency Accumulation Method" to the actual match situation will be practical.

5. 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/h and 12.0 J/kg at 5.4 km/h. This is the first study to quantify the physiological demands of a turning while running. This information may be helpful for estimating the EE of players in a match using video analysis, and for designing training programs that include turns.

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Figure Legends

Figure 1. Relationship between gross EE and turn frequency. EE, Energy expenditure; α, EE of a 180 degree turn at one running speed; f, turn frequency; running EE, the EE at constant velocity.

Figure 2. Course outline showing the running distances for each set. Participants ran back and forth between two lines at running speeds of 4.3 and 5.4 km/h.

Figure 3. Relationship between turn frequency and oxygen consumption (a), heart rate (b), and RPE (c) while running at different speeds. The slopes of the regression equations for VO_2 versus turn frequency and HR versus turn frequency were significantly different at running speeds of 4.4 and 5.4 km/h (*, $P < 0.001$). The slopes of the regression equations for RPE versus turn frequency did not significantly differ at different speeds ($P = 0.390$).

Figure 1

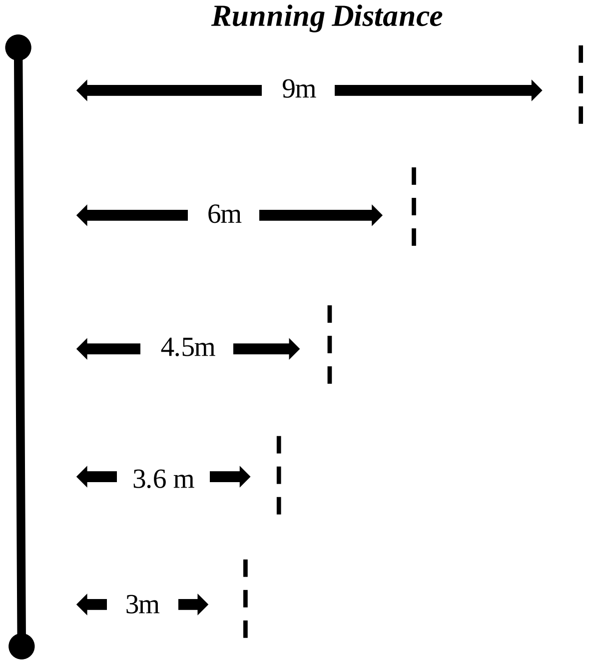


Figure 2

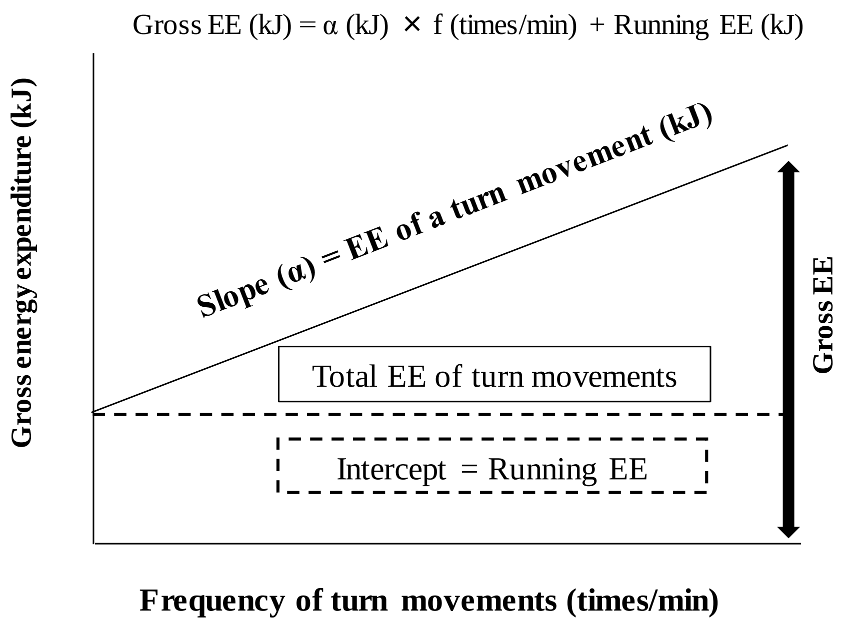
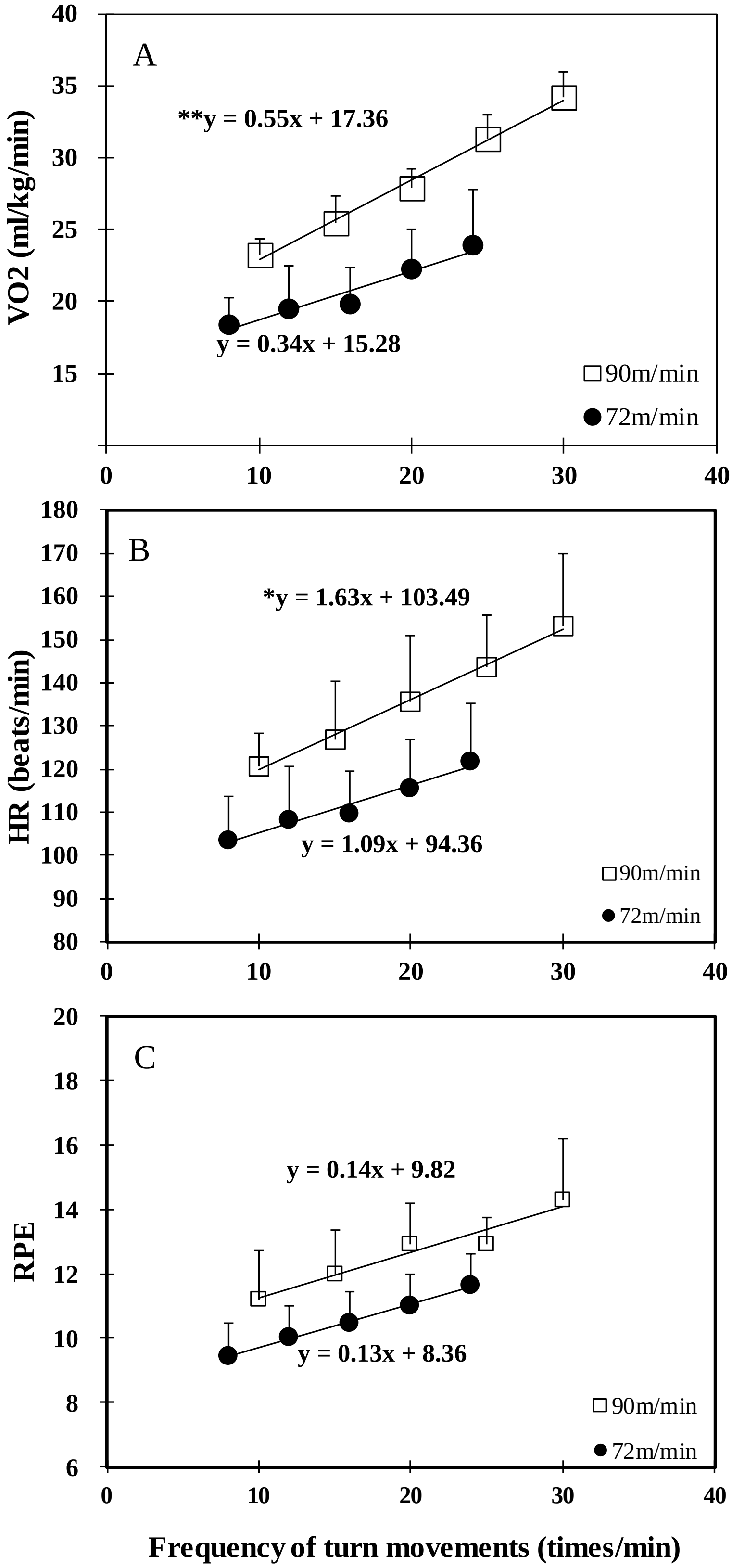


Figure 3


A
VO2 (ml/kg/min)
**y = 0.55x + 17.36
y = 0.34x + 15.28
90m/min
72m/min
B
HR (beats/min)
*y = 1.63x + 103.49
y = 1.09x + 94.36
90m/min
72m/min
C
RPE
y = 0.14x + 9.82
y = 0.13x + 8.36
90m/min
72m/min
Frequency of turn movements (times/min)

Chapter 2

The Relationship between Running Velocity and the Energy Cost of Turning during Running

Keywords Energy expenditure・change of direction・running velocity

Abstract

Ball game players frequently perform changes of direction (CODs) while running; however, there has been little research on the physiological impact of CODs. In particular, the effect of running velocity on the physiological and energy demands of CODs while running has not been clearly determined. The purpose of this study was to examine the relationship between running velocity and the energy cost of a 180° COD and to quantify the energy cost of a 180° COD. Nine male university students (aged 18–22 years) participated in the study. Five shuttle trials were performed in which the subjects were required to run at different velocities (3, 4, 5, 6, 7, and 8 km/h). Each trial consisted of four stages with different turn frequencies (13, 18, 24 and 30 per minute), and each stage lasted 3 minutes. Oxygen consumption was measured during the trial. The energy cost of a COD significantly increased with running velocity (except between 7 and 8 km/h, $p = 0.110$). The relationship between running velocity and the energy cost of a 180° COD is best represented by a quadratic function ($y = -0.012 + 0.065x + 0.008x^2$ [$r = 0.994$, $p = 0.001$]), but is also well represented by a linear ($y = -0.228 + 0.152x$ [$r = 0.991$, $p < 0.001$]). These data suggest that even low running velocities have relatively high physiological demands if the COD frequency increases, and that running velocities affect the physiological demands of CODs. These results also showed that the energy expenditure of COD can be evaluated using only two data points. These results may be useful for estimating the energy expenditure of players during a match and designing shuttle exercise training programs.

Introduction

Ball sports such as soccer, basketball, handball, rugby, lacrosse and tennis place large metabolic demands on players. For example, video analysis of Italian "Serie A" matches showed that the average distance covered during 56 soccer matches was 10,950 ± 1,044 m (range; 8,683 to 13,533 m) per player per match [1]. It is estimated that the total energy expenditure of a soccer player during one match is about 1,200–1,500 kcal [2-6], and these values include not only the energy utilized for the distance run, but also the energy requirements of other movements associated with soccer activities [7]. Professional soccer players in the FA Premier League perform more than 700 turns during a match [8]. Turning is a maneuver that includes a decrease and then an increase in velocity to change the velocity [9]. A COD while running requires applying additional force to the ground to direct the original momentum of straight running toward a new direction [10,11]. Thus, CODs while running should require some additional energy.

There has been little research on the physiological response to a COD while running. A few previous studies have compared the physiological response to straight-line running with the response to shuttle running [12–15]. These studies showed that the inclusion of COD during submaximal [14] and high-intensity [13] running created a greater physiological demand (higher oxygen uptake [VO_2]), heart rate [HR] and blood lactate [La]) than forward running without CODs. Although the results of these previous studies suggest that running with 180° CODs is more physiologically demanding than straight running, it is not clear what the actual energy cost of a COD is. Since CODs during running typically happen very quickly, it is difficult to estimate the energetic cost related to this maneuver.

We recently developed the different frequency accumulation method (DFAM) for evaluating the physiological demands of turning while running. This method is a graded test in which subjects perform 180° turns at different frequencies while running at a fixed average velocity; this allows estimation of the energy cost of turning by measuring the oxygen consumption and comparing it with that of steady-state [16]. However, we initially investigated the energy cost of turning while running at two low velocities (4.3 and 5.4 km/h). Thus, further study is needed to examine the relationship between running velocity and the energy cost of a COD (i.e., whether the energy cost is affected by running velocity) and to quantify the energy cost of a COD at higher velocities.

The aims of this study were 1) to compare the physiological demands of straight-line running and running with 180° CODs, 2) to examine the validity of the DFAM to calculate the energy cost of a change of direction, and 3) to establish an equation describing the energy cost of a 180° COD as a function of running velocity.

Methods

Subjects

Nine male university students who were well-trained lacrosse players and practiced 5 days per week volunteered to participate in this study. Table 1 shows the descriptive characteristics of the subjects. Subjects had been practicing lacrosse for more than 8 months, but before starting lacrosse they had played ball games such as volleyball, baseball, tennis, and basketball) for more than 6 years; therefore, it was expected that this population would be familiar with performing CODs while running. All of them were free of any injury that might influence their athletic performance. The subjects were advised to abstain from strenuous exercise on the day before each experiment and to maintain their normal daily nutritional intake during the study. This study was approved by the Ethics Committee of Fukuoka University, Fukuoka, Japan (12-02-02), and written informed consent was obtained from all participants. This study followed the principles of the World Medical Association Declaration of Helsinki, the Ethical Principles for Medical Research Involving Human Subjects, and the Ethical Guidelines for Epidemiological Research provided by the Ministry of Education, Culture, Sports, Science and Technology and Ministry of Health, Labour and Welfare, Japan.

DFAM

Our previous study established the DFAM as a novel approach to evaluating the instantaneous physiological demands of turning while running. Using this method, we found that the gross energy expenditure (EE) increased linearly with COD frequency (Figure S1). The EE of a COD (turn cost) was expressed as the slope of the regression of gross EE versus turn frequency, and the intercept of the regression line was the EE of running at a constant velocity. The EE of a turn included the linear deceleration to slow down the forward velocity as the runner initiated the COD, and the linear acceleration to get the runner back up to the target running velocity after the body had been rotated. Thus, this method made it possible for us to calculate the net EE of a turn while at a constant running velocity.

Experimental protocols for assessing the EE of a COD

Each subject performed six shuttle exercise trials at different average running velocities. The running velocities in this study were 3, 4, 5, 6, 7 and 8 km/h. The CODs were performed using the sidestep cutting technique, in which the runner turns away from the side of the supporting leg [10,11,17]. The first trial was conducted after more than 2 days of instruction and practice, and before every trial the subjects were reminded how to perform the 180° CODs and practiced the turning technique for a few minutes. The trials were conducted over a one-month period and the order in which the participants performed the trials was randomly determined. If 3- or 4-km/h shuttle exercise was selected, then another trial was performed after taking a rest of at least 20 min. All other trials were performed on separate days. All participants were instructed to get at least 6 hours' sleep before the test days and to avoid food, caffeine, tobacco products, and alcohol for 3 hour prior to the trials, and were asked to wear the same indoor sports shoes each time. The experiments were conducted in an indoor facility with polyvinyl chloride flooring, and the temperature during the experiments ranged between 22 and 24 °C.

The trial protocol is shown in Figure 1. Each trial consisted of four stages of different 180° COD frequencies. Each stage lasted three minutes, with a one-minute rest between stages. The COD frequencies in each stage were 13, 18, 24 and 30 per minute. However, the 8 km/h only trial had three stages and the COD frequencies were 13, 18, and 30 per minute. CODs were performed so that the runner turned an equal number of times in both directions. Running distances were determined by the turn frequencies and average running velocities. A metronome was used to pace the participants at average running velocities and to indicate the moment of COD (DM-17; Seiko Digital Metronome, Seiko Corp, Tokyo, Japan). Participants were asked to run a certain distance just within determined beats, but at their own preferred stride length, which we particularly did not determine, and they ran back and forth freely. For example, when subjects performed the 180° CODs 30 times at each speed, they had to run the distances determined by each running speed in just 2 seconds, and perform CODs at the same time (i.e: when the subject performed the 180° CODs 30 times at 6 km/h (100 m/min), the running distance was 3.33 m with CODs every 2 seconds (60 beats per minute : bpm, 1 beat is 1second). Thus, the metronome was used to provide an auditory key to the subjects to fix the timing of CODs and to regulate the running pace exactly and they were allowed to use their own preferred stride length and frequency.

Gas exchange measurements were carried out during the trials (ARCO 2000, ARCO System, Chiba, Japan). VO_2 was assessed for the final 1 minute of each stage of the trial. Heart rate (HR) was measured during the last 30 seconds with a Polar heart rate monitor (CE0537, Polar Electro, Kempele, Finland). Subjects were asked to provide a rating of perceived exertion (RPE) using the Borg scale [18] after each stage. A blood sample was collected from the earlobe for determination of blood lactate concentration (La) at one minute after each trial. These samples were collected after cleaning the earlobe with alcohol and were immediately analyzed using a portable blood lactate analyzer (Lactate pro, Arkray, Japan).

Aerobic capacity test

The aerobic capacity test consisted of 6 incremental velocity stages (from 3 to 8 km/h) and ramp increments during treadmill exercise. This test had two purposes: 1) to determine steady-state oxygen consumption at from 3 to 8 km/h and 2) to determine peak oxygen uptake (VO_2 peak). The aerobic capacity test was conducted within one month after the EE test. Subjects started with a warm-up phase consisting of 2 min of walking at 3 km/h. After the warm-up, treadmill velocity was then increased by 1 km/h every 3 min until 8 km/h was reached (6 stages total). Thereafter, to measure VO_2 peak, running velocity was immediately increased to 10 km/hr, then increased by 1 km/hr every 1 min until reaching12 km/h. Following this, the velocity of 12 km/h was held constant while the treadmill grade was increased by 2% every 1 min. The test was continued until subjective exhaustion was achieved, and VO_2 values were recorded continuously throughout the trial. Expired gas was analyzed by mass spectrometry (ARCO 2000, ARCO System, Chiba, Japan). The highest VO_2 over 1 minute was regarded as the VO_2 peak. We also obtained the HR value during the last 30 seconds and RPE immediately after the test and the La value after 1 min. VO_{2max} was assumed to be reached when the oxygen uptake plateaued or two of the following four criteria were achieved: 1) reaching at least 8 mmol/L La concentration; 2) reaching the age-adjusted 90% of maximal HR; 3) reaching at least an RPE value of 18; or 4) reaching a respiratory exchange ratio (RER) greater than 1.10 [19]. The subjects in the study fulfilled two of four criteria (La: 9.0±2.2, RPE: 19.1±0.6, HR 194.4±8.4, RER: 1.13±0.06).

Energetic measurements

EE during both exercise tests was measured by collecting an expired gas sample through a facemask. Respiratory gas analysis was conducted using the mixing chamber method 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 min. At the beginning of each trial the 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.

Statistical analyses

All analyses were conducted using SPSS software version 20 (SPSS, IBM, Armonk, NY, USA). All values are expressed as mean±standard deviation (SD). Linear regression analyses were used to calculate slopes and intercepts for gross EE against turn frequency at each running velocity. One-way ANOVA was used to compare the slope of the VO_2 that indicates the cost of a COD performed during shuttle exercise at different running velocities. Post-hoc Bonferroni tests were used to determine the significance of differences. Regression line and curve analysis was performed to predict the cost of CODs at different running velocities and expresses the relationship between the energy cost of turning and running velocity. These regression equations were based on the average data for all subjects at running velocities of 3–8 km/h. The six data points for running velocity were plotted on the x-axis and the energy cost of COD values were plotted on the y-axis. The relationship between the VO_2 of treadmill running and VO_2 of the intercept of regressions between VO_2 and COD frequency at 3–8 km/h were determined by Pearson's product-moment correlation coefficients and compared by paired t-test. Differences were considered significant at an alpha level of $P < 0.05$.

Results

All participants successfully completed all trials. Table 2 shows the gross VO_2 of different COD frequencies and the VO_2 of treadmill running at 3–8 km/h running velocities. The linear regressions of COD frequency and VO_2, HR, and RPE were obtained for each running velocity (Figure 2). As running velocity increased, the energy cost of a COD also increased. At running velocities of 3, 4, 5, 6, 7, and 8 km/h, the energy cost of a COD was 0.27 ± 0.03, 0.35 ± 0.05, 0.48 ± 0.10, 0.68 ± 0.08, 0.87 ± 0.13, 0.99 ± 0.14 (ml/kg), respectively (Figure 3). The cost of changing direction did not differ between running velocities of 7 and 8 km/h (7 vs 8 km/h, $p = 0.110$).

The average energy cost of a COD versus running velocity in all subjects was best expressed by a quadratic model ($y = -0.012 + 0.065x + 0.008x^2$ [$r = 0.994$, $p = 0.001$]), but was also well expressed by a linear model ($y = -0.228 + 0.152x$ [$r = 0.991$, $p < 0.001$]). Blood lactate values 1 min after each trial were 1.0 ± 0.2, 1.1 ± 0.2, 1.2 ± 0.4, 1.7 ± 0.6, 2.8 ± 0.8, 4.7 ± 1.7 ml/kg at 3–8 km/h, respectively.

In order to confirm the validity of the hypothesis that the intercept of the regression line of VO_2 versus COD frequency corresponds to the VO_2 of treadmill running, we examined the correlation and conducted paired t-tests to assess the relationship between the VO_2 of treadmill running and the intercepts of the regression line for each running velocity. There was a significant correlation between the VO_2 of treadmill running and the intercepts of the regression of VO_2 versus COD frequency at each running velocity ($r = 0.966$, $p = 0.002$) (Figure 4), and these were not significantly different (paired t-test, $p = 0.582$).

Discussion

The purpose of this study was to investigate the difference in energy demand between running with 180° CODs and straight-line running and, in particular, the influence of running velocity on the VO_2 associated with a 180° COD and the validity of the DFAM. We also suggest a protocol for measuring the energy cost of a turn more easily. The results of this study show that as running velocities increase, physiological responses such as HR, RPE, La, and the VO_2 of CODs also increase.

In recent years a few studies have focused on different physiological responses to running with 180° CODs and running without turning. Dellal et al. (2010) compared physiological responses such as HR and La in soccer players during intermittent straight-line running and intermittent shuttle exercise with 180° turns performed at vVO_{2max} (maximal aerobic velocity) running velocities and covering the same distances [13]. The values of HR and La during shuttle exercise were higher than those during straight running. When running velocities were adjusted for maximal O_2 uptake during a straight-line incremental protocol, the pulmonary VO_2 for shuttle running was higher than for straight running [14]. A recent study also showed that when comparing shuttle exercise over a 3.5-m and a 7.0-m course at the same average running velocities and for the same total distances covered, the 3.5-m shuttle exercise induces a greater physiological response [20]. This occurs because of the greater number of 180° CODs required for the 3.5-m course. Our results also indicate that the VO_2 responses to running with turning were greater than for straight running at each running velocity (Table 2). Table 3 illustrates the values of VO_2 at four different COD frequencies for the same average running velocities and compares them to treadmill running at the same velocites. The gross VO_2 of running including 30 CODs/minute was approximately twice the gross VO_2 of treadmill running at the same velocity. For example, in general, 3 km/h is a very low running velocity, but 30 CODs per minute at 3 km/h has similar metabolic demands to straight running at 6 km/h. In addition, the VO_2 at 8 km/h with 30 CODs per minute was close to VO_{2max}, although a running velocity of 8 km/h would be classified as “low-intensity” activity in a ball game [21]. The estimated energy cost during the acceleration phase of running is higher than the energy cost while running at a constant velocity [22]. A COD while running requires a phase of deceleration and acceleration and eccentric and concentric muscle contraction [9], which generates a greater physiological load [12,13,14,23]. These results indicate that running with CODs requires extra energy, even when running at a very low velocity.

One of the findings of this study is the equation demonstrating the relationship between VO_2 and COD frequency, which allows the energy cost of a 180° COD while running at different velocities to be quantified. Our results show a linear relationship between gross VO_2 and COD frequency at running velocities of 3–8 km/h, and the slope of the regression line indicates the energy cost of a COD while running [16]. Also, the cost of a COD increased as running velocity increased. The estimation of the energy cost of a COD is expressed by the regression equations of the relationship between energy cost of a COD and running velocities (Figure 3). Although this relationship is best represented by a quadratic function ($r = 0.994$), it is not similar to that of the linear regression equation at 3–8 km/h ($r = 0.991$). The values that we reported for the energy cost of a COD at the two running velocities used in our previous study were comparable to the values obtained from the quadratic equation of the relationship between running velocity and turn cost at similar running velocities in this study. The mean VO_2 of a turn in the previous study was 0.34 ± 0.13 ml/kg at 4.3 km/h and 0.55 ± 0.09 ml/kg at 5.4

km/h. When the same running velocities were used in the quadratic equation, the VO_2 of a 180° turn was similar to these previously reported values, (0.42 ml/kg at 4.3 km/h and 0.57 ml/kg at 5.4 km/h). At the level of the individual participants, both linear and curved relationships between the EE of a COD and running velocity were observed. The energy cost of a COD may differ between individuals because of differences in COD technique, stature and training volume [14,24]. It is possible that the energy cost of a COD performed by ball game players may be lower than that of players of other sports because ball game players perform CODs regularly, which may affect the results. Thus, the equation we have identified is most likely suitable for ball game players.

As running velocity increases, the blood lactate values increase. An earlier study has reported similar results [13]. The 180° COD with a higher running velocity would require more energy to change the velocity (for both deceleration and acceleration) and additional muscular action, possibly inducing a glycolytic contribution [13]. The standard deviations of blood lactate values also enlarge as running velocity increases. There will be less deviation among baseline La values and more deviation as La accumulates. This is probably because blood lactate accumulation is highly related to VO_2 peak [25]. The VO_2 peak of subjects in this study ranged from 47.0 to 63.8 ml/kg/min; therefore, blood lactate accumulation would differ between individuals the same exercise intensity. Further studies of the differences in energy cost of turning in players of various sports and body compositions are needed.

We hypothesized that the intercept of the regression line between gross VO_2 and turn frequency would correspond to the VO_2 of a steady-state at a constant running velocity. In our previous study we did not compare the VO_2 of the intercept to the actual VO_2 of forward running at steady state. In this study, the VO_2 was measured at each running velocity on the treadmill, and the VO_2 of the intercept was then compared with the measured value. It is well known that VO_2 increases linearly as running velocity increases [26,27]. Our results demonstrate that the VO_2 of the regression intercept also increases with running velocity. There was a strong correlation between the VO_2 of the intercepts and the measured VO_2 (Figure 4), and these values did not significantly differ (paired t-test, $p = 0.582$). These data suggest that the intercept of the regression line very closely approximates the actual VO_2 of steady state running at the same running velocity and confirm that the DFAM is a reasonable method for evaluating the energy cost of CODs while running.

In addition, both the previous study and the present one show a linear relationship between gross VO_2 and turn frequency. Therefore, turn cost can be calculated easily from only two data points (i.e., the cost of a COD can be evaluated by one treadmill and one turn trial session). We compared the energetic cost of a COD calculated using two data points (VO_2 of treadmill running and 30 times COD frequency) with the cost of a COD calculated using five points (VO_2 of treadmill run and running with four different turn frequencies) at 3–8 km/h (Figure 5); there was a significant correlation between both calculated values ($r = 0.99994$, $p < 0.00001$) and they were not significantly different ($p = 0.694$). These results indicate that the energy cost of a turn can be calculated accurately using only two data points. This will facilitate further investigation of the energy costs of CODs at various running velocities.

One method for estimating the EE of soccer players is to calculate it from only the distance covered by the player during a single soccer match [28]. However, some researchers have commented that estimating EE from distance covered may underestimate the actual value because extra energy demands associated with soccer activities such as turning, jumping, dribbling and performing soccer skills are not accounted for [7,29,30]. This suggests the need to include the energy costs of ball handling and additional energy cost of movement. Reilly and Ball demonstrated the additional energy cost of dribbling a ball on a treadmill compared with running at the same speed alone [31]. In this study, we relate the additional energy cost of turning while running by fitting an equation to our measured EE from turning at different running velocities. This equation may allow for corrections to be made to the EE calculated from distance covered in soccer match and account for underestimation of the extra energy costs of maneuvers associated with the ball game.

Conclusion

In summary, we used expired gas samples to measure the physiological response to running with 180° CODs under steady-state conditions. Running with CODs was more physiologically demanding than straight running at the same average running velocities. These results also provide further confirmation that the DFAM is a reasonable method for investigating the energy cost of CODs, and that running velocity affects the energy cost of CODs. Our results also suggest that the energy cost of a COD can be calculated using only two VO_2 measurements.

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Table and Figure

Table 1. Characteristics of experimental subjects (n = 9).

Age (years)	Height (cm)	Weight (kg)	VO_2 peak (ml/kg/min)
20.6 ± 1.2	169.6 ± 3.6	65.9 ± 9.3	58.0 ± 5.5

Table 2. Mean gross VO_2 at different COD frequencies and the VO_2 of treadmill running at velocities of 3 to 8 km/h.

Running velocities km/h	Treadmill VO_2 (ml/kg/min)	13turns/min (ml/kg/min)	18turns/min (ml/kg/min)	24turns/min (ml/kg/min)	30turns/min (ml/kg/min)
3	13.4 ± 1.0	18.2 ± 1.9	19.3 ± 2.0	21.4 ± 2.0	22.7 ± 1.8
4	15.2 ± 1.3	21.9 ± 2.4	23.8 ± 1.8	25.8 ± 2.4	28.0 ± 2.5
5	18.7 ± 1.3	24.2 ± 1.9	27.1 ± 2.1	29.4 ± 2.0	32.5 ± 2.9
6	22.0 ± 1.2	29.2 ± 1.7	32.3 ± 1.7	36.6 ± 2.1	40.8 ± 2.5
7	24.8 ± 1.2	33.9 ± 1.4	36.9 ± 1.1	42.6 ± 1.9	48.4 ± 2.3
8	27.3 ± 1.5	38.4 ± 1.9	43.6 ± 2.1	-	55.2 ± 2.7

COD, change of direction; VO_2, oxygen consumption.

Table 3. Comparison of straight and shuttle running velocites for the same VO_2 demands.

Running velocity km/h	Treadmill (km/h)	13 turns/min (km/h)	18 turns/min (km/h)	24 turns/min (km/h)	30 turns/min (km/h)
3	3.1	4.8	5.2	5.9	6.4
4	3.8	6.1	6.7	7.4	8.2
5	5.0	6.9	7.8	8.7	9.7
6	6.1	8.6	9.7	11.1	12.5
7	7.1	10.2	11.2	13.2	15.2
8	7.9	11.7	13.5	-	17.5

VO_2, oxygen consumption.

Figure legends

Supplemental Figure 1. Relationship between gross energy expenditure and COD frequency. COD, change of direction; EE, energy expenditure; α, EE of a 180° COD at one running velocity; f, COD frequency; running EE: EE at constant velocity.

Figure 1. (A) Shuttle exercise protocol. Each stage lasted 3 min, with a 1-min rest between stages. COD frequencies of each stage were 13, 18, 24 and 30 CODs per minute. **(B) EE of a COD while running.** Extra energy expenditure occurs every time a COD is performed. The figure shows the estimation for all turn frequencies over 10 seconds. COD, change of direction; EE, energy expenditure.

Figure 2. Comparison of physiological responses and RPE while running at different velocities. Relationship between turn frequency and oxygen consumption (A), heart rate (B), and RPE (C), while running at different velocities. HR, heart rate; RPE, rating of perceived exertion; VO_2, gross oxygen consumption

Figure 3. Relationship between running velocities and energy cost of a turn. Values are averages. The relationship was expressed by both an approximate quadratic ($r = 0.994$, $p = 0.001$, solid line) and a linear model ($r = 0.991$, $p < 0.001$, dashed line).

Figure 4. Relationship between actual and estimated running VO_2 at different running velocities. The VO_2 of straight running and the intercept of the linear regression VO_2 at 6 different running velocities (3–8 km/h) were significantly correlated ($r = 0.966$, $p = 0.002$). VO_2, gross oxygen consumption.

Figure 5. Comparison of turn cost for different data points. There was strong correlation ($r = 0.99994$, $p < 0.00001$) between the slopes of regression lines drawn using two data points and five data points to evaluate the energy cost of a COD. The slope of the regression line of gross VO_2 and the graded COD frequency test indicates the energy cost of a COD while running. COD, change of direction; VO_2, gross oxygen consumption.

Supplemental Figure 1.

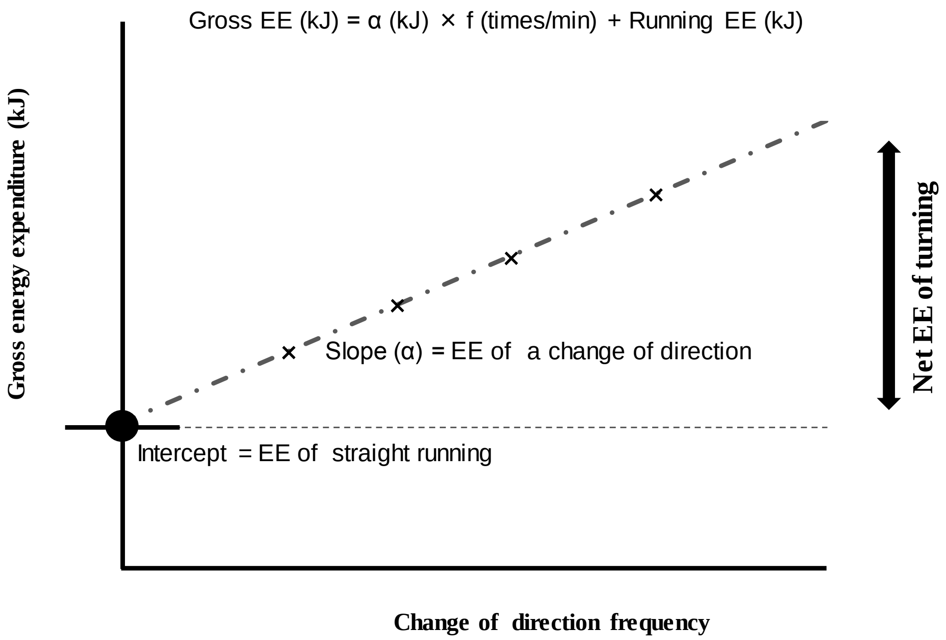


Figure 1a

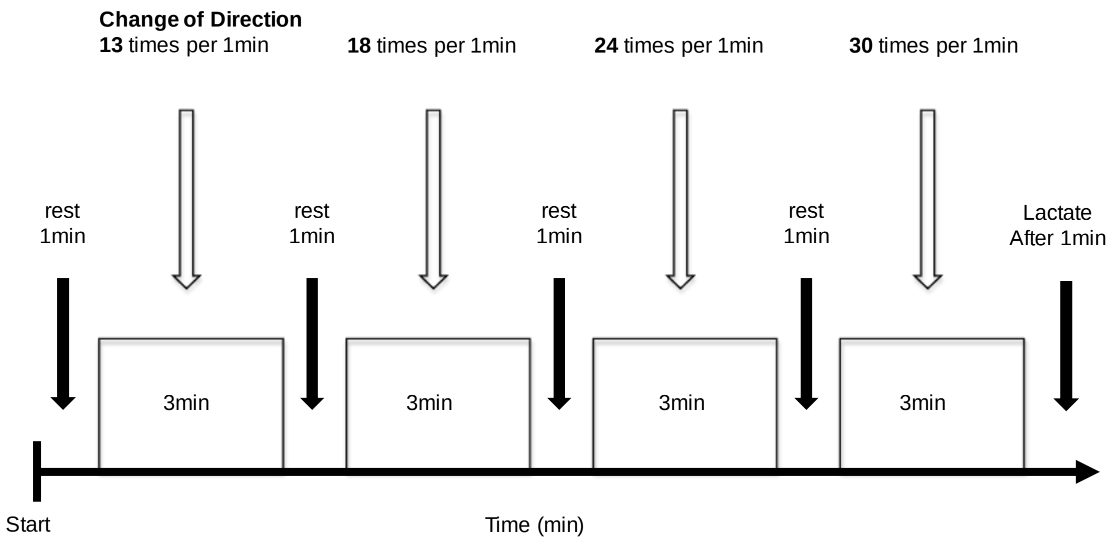


Figure 1b

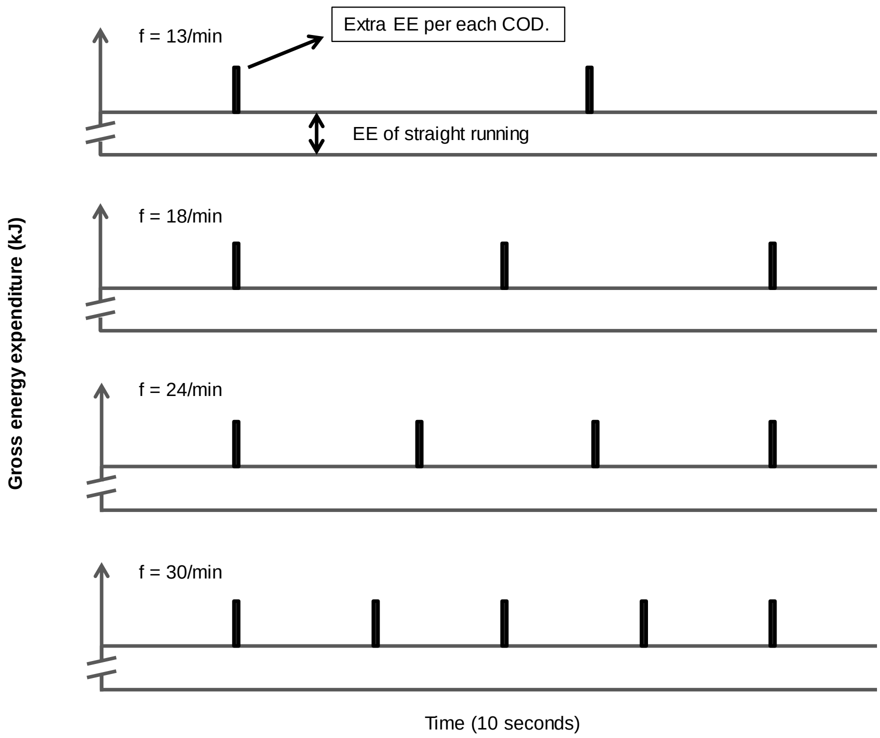
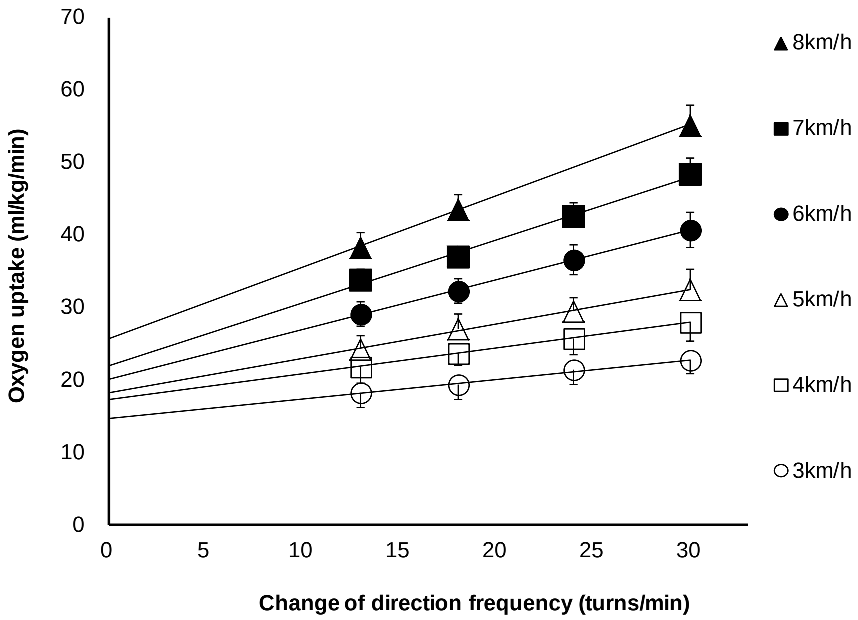


Figure 2a



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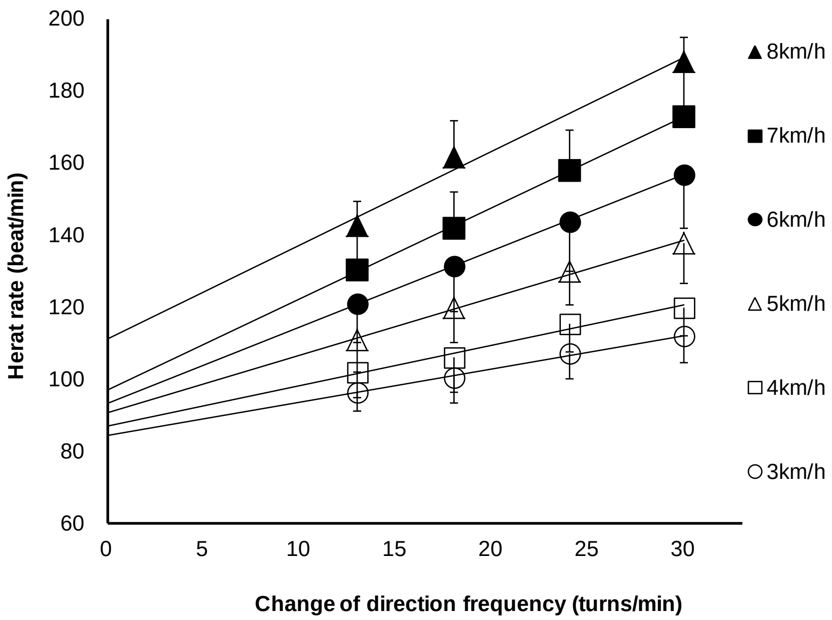

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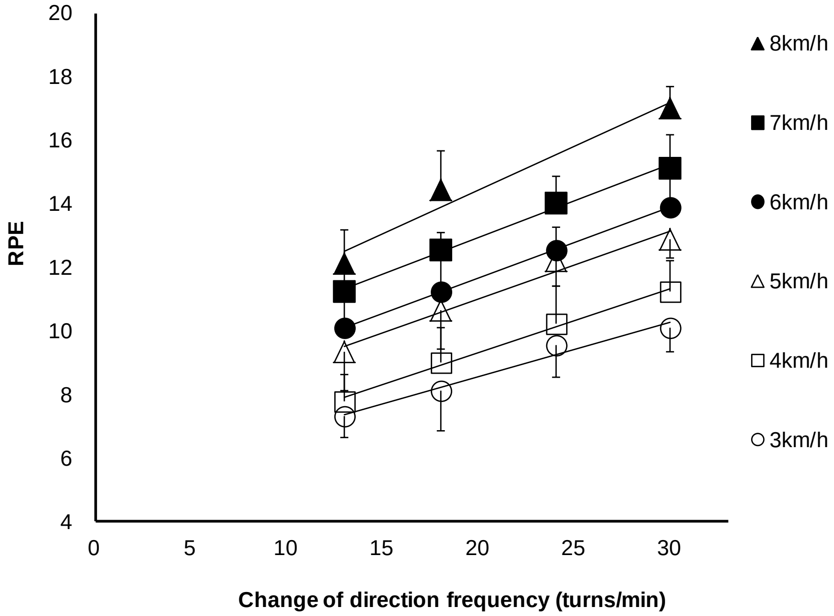


Figure 3

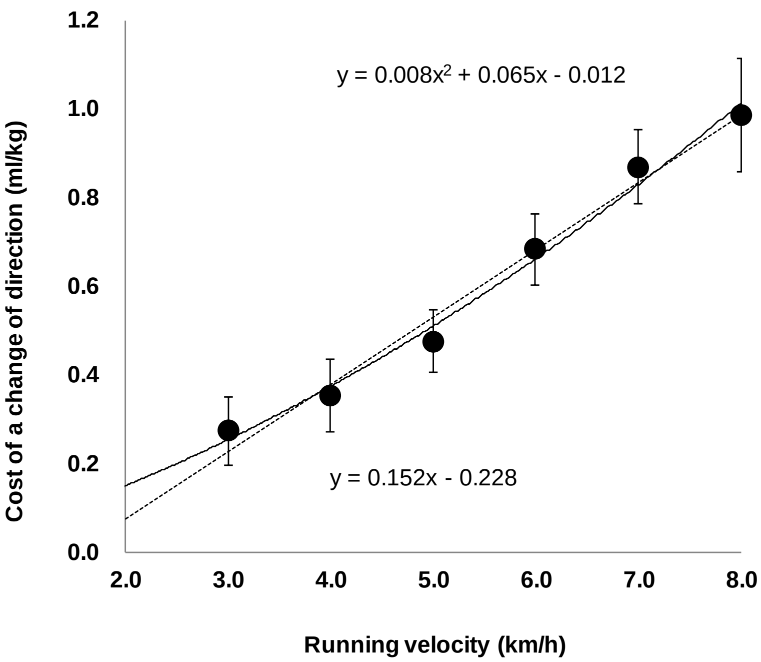


Figure 4

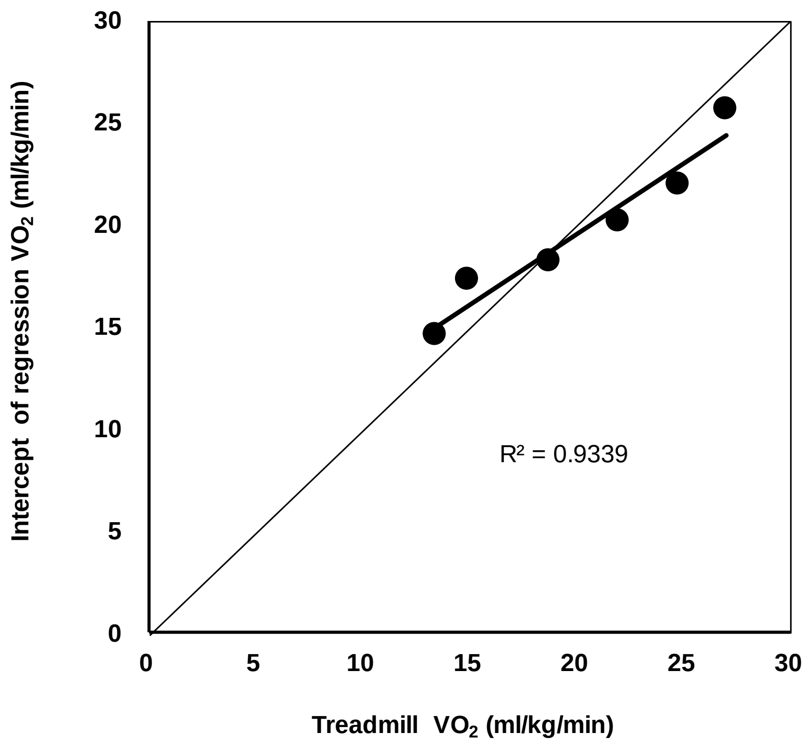
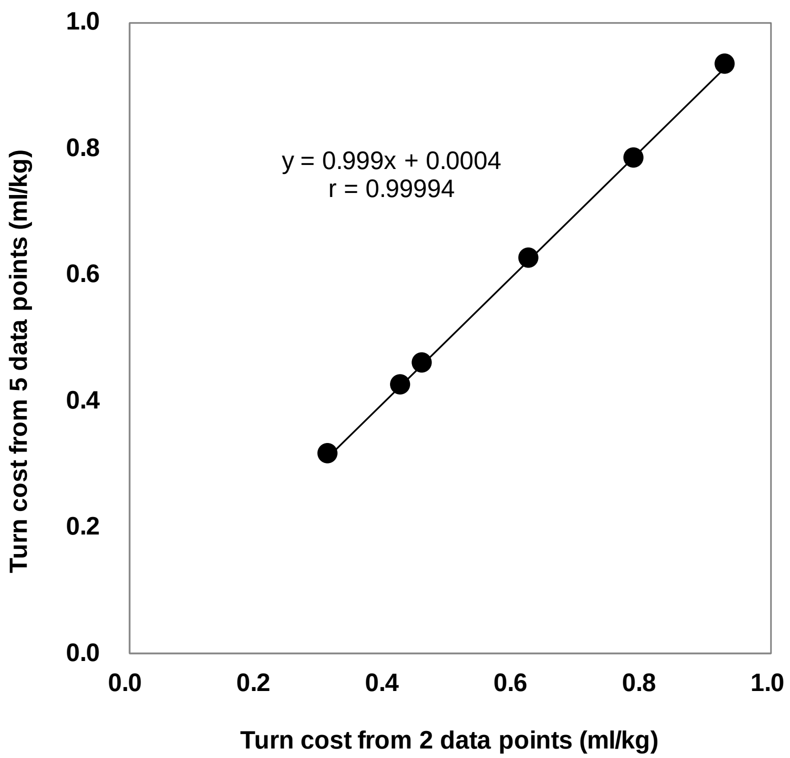


Figure 5



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