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Research Article

Determine the Foot Strike Pattern Using Inertial Sensors

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From biomechanical point of view, strike pattern plays an important role in preventing potential injury risk in running. Traditionally, strike pattern determination was conducted by using 3D motion analysis system with cameras. However, the procedure is costly and not convenient. With the rapid development of technology, sensors have been applied in sport science field lately. Therefore, this study was designed to determine the algorithm that can identify landing strategies with a wearable sensor. Six healthy male participants were recruited to perform heel and forefoot strike strategies at 7, 10, and 13 km/h speeds. The kinematic data were collected by Vicon 3D motion analysis system and 2 inertial measurement units (IMU) attached on the dorsal side of both shoes. The data of each foot strike were gathered for pitch angle and strike index analysis. Comparing the strike index from IMU with the pitch angle from Vicon system, our results showed that both signals exhibited highly correlated changes between different strike patterns in the sagittal plane ($r = 0.98$). Based on the findings, the IMU sensors showed potential capabilities and could be extended beyond the context of sport science to other fields, including clinical applications.

1. Introduction

Running and walking gait can be separated into two phases with respect to the lower limbs kinematics, such as swing and stance phases. Swing phase is known as alternating sequences of nonsupport, and the stand phase can be referred to as the sequence of support. Specifically, stance phase takes place when a plantar portion of the foot contacts the ground and is finished with the toe off the ground. Recently, foot strike or landing strategies have stimulated considerable collision of scientific interests in the foot strike patterns among barefoot and shod runners [1–3]. Two major common strike patterns can occur during running. The first one is heel strike at which stage the heel contacts the ground first (i.e., most shod runners); the second one is forefoot strike at which stage the ball of the foot lands the ground before the heel (i.e., sprinters and most barefoot runners) [4]. This brings up the ideas that different strike patterns would be a key factor that contributes to the inefficient and injurious foot strike technique.

From the biomechanical point of view, different strike pattern plays an important role in the prevention of potential injury risk in running. In general, heel strike pattern produces a significant impact transient of the vertical ground reaction force at the moment the heel collides with the ground, whereas the forefoot strike pattern generates a minimum impact force but considering less efficiency. Recent studies showed that heel strike was associated with higher rates of running injuries (e.g., tibial stress fractures) and impacts as the result of inefficient shock absorption or inefficient compensations of muscles and bones [5, 6]. Shih et al. also showed that forefoot runners had lower loading rate that could be considered as an important factor for running injuries [7, 8]. Consequently, knowing different strike techniques might be a key factor to protect the feet and lower extremity from potential injury risks in running.

Traditionally, strike pattern determination was conducted commonly in the laboratory using 3D motion analysis

system with cameras. A number of reflective markers were attached over the participants' bony landmarks in accordance with specific marker setup. In addition, the coordination data collected from these markers were used to calculate the parameters of research interest, such as different angle of joints at landing, joint range of motion (ROM), and time interval of landing point [9, 10]. Lieberman et al. used an infrared kinematics system (Qualysis) with force plates to investigate different strike patterns and collision forces for barefoot runners versus shod runners. They found that two types of habitual runners used different strike patterns and barefoot runners often landed on the forefoot, whereas shod runners used heel strike mostly [2]. In addition, barefoot runners produced smaller collision forces by using forefoot strike than shod rear foot strikers on the hard surfaces. Therefore, Shih et al. used similar way to investigate which foot strike patterns are important to barefoot or shod condition in running [8]. They suggested that the lower limbs could gain more compliance when running with a forefoot strike and that habitually shod runners might get injured easily when they ran barefoot but still maintaining their heel strike pattern. The motion tracking or motion capture system has been recognized to provide the human kinematic data. However, the procedure of using motion analysis to collect the data of interest is costly and not convenient.

With the rapid development of technology, sensors have been applied in sport science field lately. Because of portability and low cost, inertial sensor has been considered as an alternative tool and has become widely used in the research of biomechanical studies [11–14]. Shih et al. showed that coordinative data from wearable motion sensors were highly correlated with the kinematic data obtained from the optical motion analysis system [15]. In addition, Shih et al. and Tong and Granat have proven that the correlation between gyroscope and Vicon® signal was very high in the sagittal plane [8, 16]. Moreover, Lee et al. proposed that the inertial measurement unit (IMU) sensors could demonstrate potential capabilities by showing its ability to identify walking, running, and jumping locomotion at different levels of intensity [12]. Nevertheless, the spatial-temporal properties of different strike patterns changed by using inertial sensors have not been proved. The purpose of this study was to determine the strike patterns at different speeds by using inertial sensors. In addition, we also investigated the similarity of the signals between inertial sensor and motion analysis system to examine the validity of sensor used in this study.

2. Materials and Methods

2.1. Participants. In this study, we recruited 6 healthy male participants (age: 25.4 ± 1.7 years; height: 175.0 ± 5.2 cm; weight: 72.4 ± 5.7 kg) without cardiovascular diseases or severe lower extremity injuries in the last 6 months. This study was approved by the Medical Research Ethics Committee and all participants completed a statement of informed consent.

2.2. Equipment. The kinematics data were collected by the 3D motion analysis system with 10 Vicon MX 13+ cameras

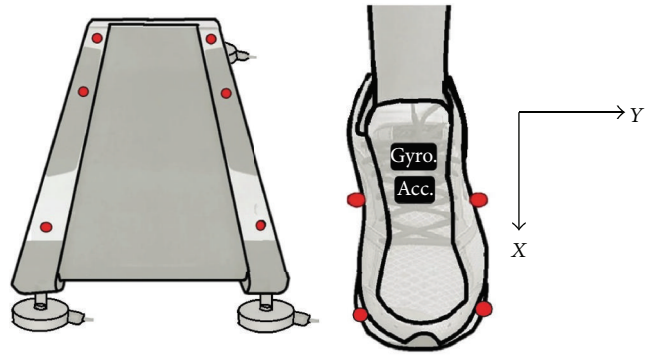

Figure 1: The setting of IMU on the foot. Arrows represent anterior axis (X) and lateral axis (Y).

at the sampling rate of 200 Hz. The software used was Nexus 1.82 (Vicon, Oxford, UK). Sixteen reflective markers (13 mm) were placed on bony landmarks according to the Plug-in Gait model (Vicon, 2002). We also put 14 additional markers (4 on left shoe, 4 on right shoe, and 6 on treadmill) to help us determine if the shoes contact the belt of treadmill (Figure 1). Two inertial measurement units (IMU) were attached on the dorsal side of both shoes; one was a tri-axial accelerometer (CXL25GP3, Crossbow, USA) and the other was a tri-axial gyroscope which was manufactured by 2 dual-axis gyro breakout boards (SEN-09412, SEN-09425, SparkFun, USA). The measurement ranges were ±25 G and ±1500 rad/s, respectively. The accelerometer was calibrated on a table by the gravity, and the angular velocity data provided by gyroscope (0.67 mv/degree/sec) was calibrated by the Vicon system. Vicon system is commonly used in robot localization experiment or biomechanical research or for experimental validation tests [2, 8, 16, 17]. The IMU was first fastened to a two-arm goniometer and on which also mounted with 2 reflective markers arranged at the corner. Then we moved the moving arm reciprocally. The goniometer orientation was recorded using Vicon system with a sampling rate of 200 Hz. The correlation between angular velocity data provided by Vicon system and IMU is $r = 0.99$.

Treadmill (MAG-7310, Magtonic, Taiwan) with 4 load cells (Delta transducer, India) set underneath the 4 corners was used to control the speed of running and to measure the vertical ground reaction force while running (Figure 1). The analog data was collected by an acquisition system (MP150, Biopac, USA) with the sampling rate of 1000 Hz.

2.3. Procedures. Participants did 5 minutes warm-up and practiced heel and forefoot strike running at self-selected speed to become familiar with different strike strategies before starting the trials. Then participants were asked to perform 2 different foot strike strategies (heel and forefoot strikes) at 3 different speeds (7, 10, and 13 km/h) on the treadmill in a random order. Each trial consists of 1-minute running and at least 2-minute rest between each trial. Fifteen-second data was recorded in the middle of one trial when the runners' gaits were steady.

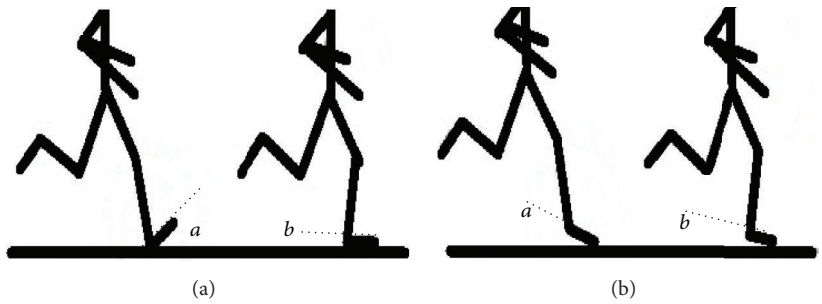

Figure 2: The pitch angles of different landing strategies ((a) heel-strike landing strategy; (b) forefoot-strike landing strategy).

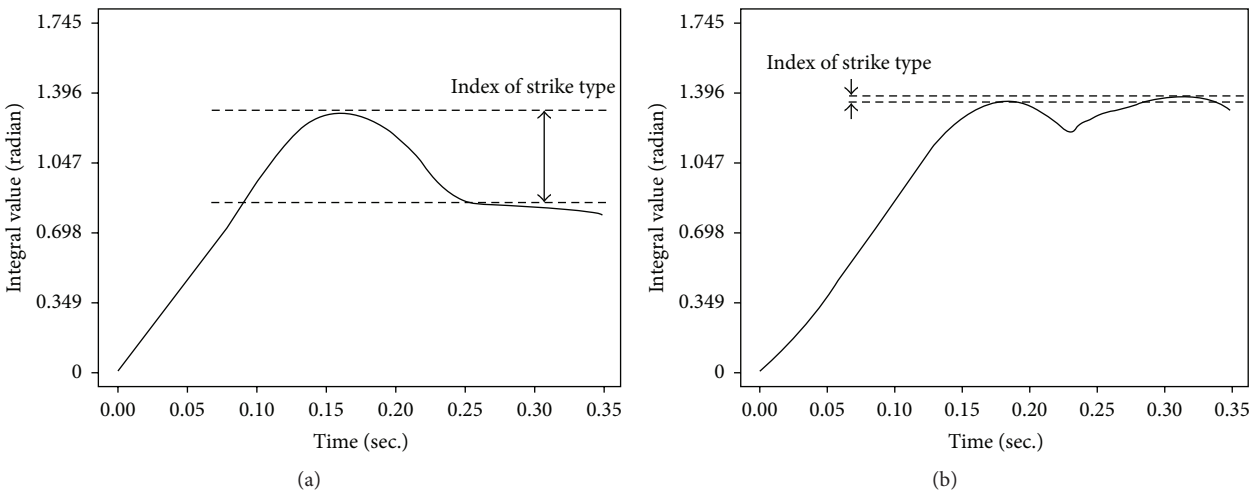

Figure 3: The correlation between the time and the integral value of angular velocity in the sagittal plane ((a) heel-strike landing strategy; (b) forefoot-strike landing strategy).

2.4. Data Collection. Three-dimensional kinematics data were collected by the motion analysis system in this study. The effects of foot strike patterns on lower limb kinematics and kinetics were mostly discussed on sagittal plane; therefore, during the landing strategy and running speed trials, the kinematic and IMU data of each foot strike from all participants were gathered for sagittal plane analysis of pitch angle and strike index at a later time. The pitch angle is the angular changes, measured by Vicon motion analysis system, in the ankle-joint sagittal plane of the swing foot from the moment the foot touches the ground until it reaches its lowest position in a strike. It can be written as

$$\text{pitch angle} = a - b, \tag{1}$$

where a is the angle formed between the dotted line and the treadmill belt at the time when the forefoot or the heel touches the belt and b is the angle formed between the dotted line and the treadmill belt at the time when the forefoot or the heel reaches its lowest position in a foot strike (Figure 2).

Strike index was used with the IMU data to assess the landing strategy parameters of each foot strike. To obtain the complete time intervals from the moment the foot touches the ground until the whole foot is on the ground, this study first identified, from the IMU data, the time when the resultant acceleration of tri-axial accelerometer reached its maximum value. Then the observation area was determined by adding 0.2 seconds and subtracting 0.15 seconds from the identified time point on each step, and by doing so, the data drift issue of integration can be minimized at the same time. To understand the correlation between the time and foot angle (θ_n) in the sagittal plane (Figure 3), the data integration was conducted on the gyroscope data in the sagittal plane within the observation area. The angle of θ_n can be calculated by digitally integrating the signal from the gyroscope (ω_n):

$$\theta_n(t+1) = \left(\omega_n(t+1) - \omega_n(t)\right) \cdot \Delta t + \theta(t). \tag{2}$$

Next, two time points, where the slope = 0, within the interval were identified. Finally, the strike index of each foot strike was obtained by subtracting the two foot angles, derived from the aforementioned two time points, in the sagittal plane.

2.5. Statistics. Pearson's Correlation Coefficient was used to analyze and calculate the linear correlation between strike index and pitch angle. When the coefficient falls in $0.7 \leqq |r| < 1$, the two variables are considered highly correlated. This study also used linear regression to predict values between the strike index and pitch angle.

Table 1: Data on the steps, strike index, and pitch angle for different speeds and landing strategies.

		Steps	Strike index (mean ± SD) (unit: radian)	Pitch angle (mean ± SD) (unit: radian)
Heel strike	7 km/hr	468	0.386 ± 0.092	0.384 ± 0.100
	10 km/hr	494	0.375 ± 0.145	0.388 ± 0.124
	13 km/hr	429	0.386 ± 0.092	0.449 ± 0.107
	Total	1391		
Forefoot strike	7 km/hr	468	−0.040 ± 0.051	−0.080 ± 0.062
	10 km/hr	472	−0.033 ± 0.058	−0.068 ± 0.057
	13 km/hr	365	−0.012 ± 0.077	−0.020 ± 0.092
	Total	1305		

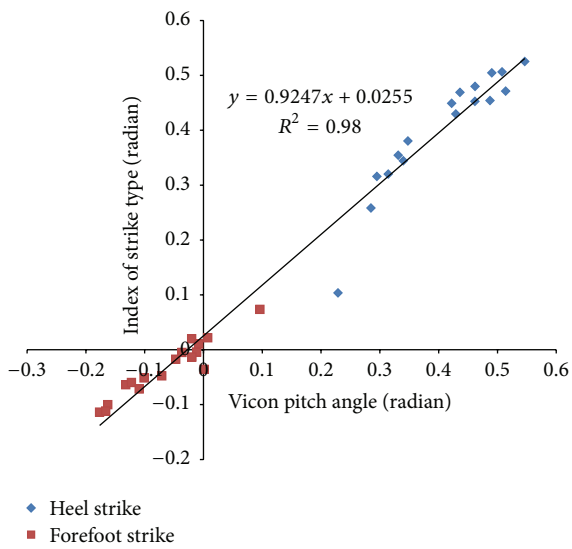

Figure 4: The correlation between strike index and pitch angle for different landing strategies.

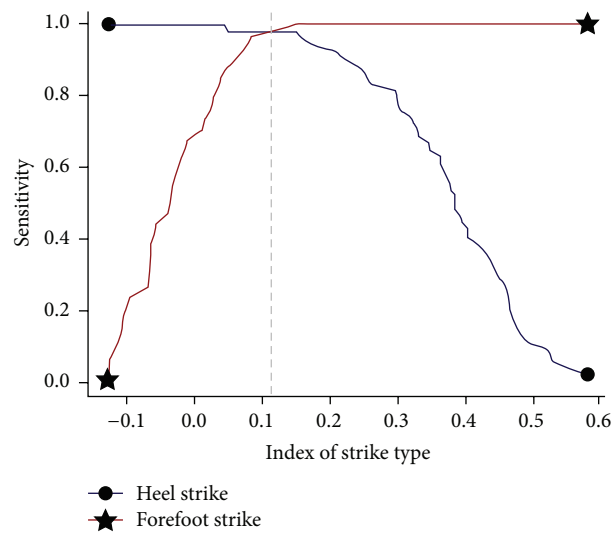

Figure 5: The correlation between sensitivity and strike index (★: forefoot strike; ●: heel strike).

3. Results and Discussion

One participant failed to complete the 13 km/hr trial, whose record was therefore excluded from the data analysis. Hence, the study analyzed the data of different landing strategies from 6 participants for the 7 km/hr and 10 km/hr trials and from 5 participants for the 13 km/hr trial. Altogether, there were 1391 steps of heel strike and 1305 steps of forefoot strike gathered for analysis. The data of steps, strike index, and pitch angle were shown in Table 1.

To get the strike index values that can best differentiate between the forefoot strike and heel strike, this study analyzed the strike index of all participants on each trial and had the data presented in a scattergram. The result suggested that the strike index and pitch angle were highly correlated (Figure 4) according to the Pearson's Correlation ($r = 0.99$). The linear regression equation is $y = 0.9247x + 0.0255$, where y is the strike index and x is the pitch angle. The decisive coefficient is 0.98.

By reference to the Van-Westendorp Method [18], this study also analyzed the values of strike index and the sensitivity on identifying landing strategies (Figure 5). Each value was considered a boundary line; any data falls below the line was attributed to forefoot strike, and any data above the line was attributed to heel strike. The percentage of attribution accuracy represented the sensitivity in identifying landing strategies. The analysis of strike index and sensitivity in identifying landing strategies showed that the sensitivity reached its optimal value when the strike index was 0.115.

4. Discussion

In the current study, our purpose was to measure the kinematic changes of the foot strike strategies with different running speeds (7–13 km/h) and also to compare the similarity of the signals between inertial sensor and motion analysis system to validate the application of the IMU sensors in strike pattern detection. The forefoot and heel strike patterns in 3D motion analysis system were determined on the basis of the sixteen reflective markers placed on bony landmarks, whereas two IMU were attached on the dorsal side of the shoes. The Vicon system was used to investigate the contribution of kinematics of gait patterns (e.g., foot angle and strike patterns) and its interactions with IMU also provided a potential link between the development of microelectromechanical systems and facilitating data collection under free-living conditions

[11, 12]. Furthermore, we used the characteristics of strike patterns in a gait cycle to ensure that the sensitivity of cutting point was accurate enough to differentiate landing strategies [19, 20].

Comparing the strike index from IMU with the pitch angle from Vicon system during stance phase in running, our results clearly showed that IMU and Vicon signals exhibited high correlated changes between different strike patterns in the sagittal plane ($r = 0.98$). This finding revealed that, during the stance phase of running cycle, the kinematic data collected from either forefoot strike or heel strike strategy by IMU device with sensor fusion can be a valuable reference for strike pattern detection [15, 16]. This highly correlated result between IMU and motion system was also found by Shih et al. using a similar approach to determine the kinematic changes of the foot during intense running [8]. Given that the application of IMU device placed on the foot to replace the motion system has yet to be fully explored, using IMU for strike patterns detection could be a valuable reference based on the results of our study.

Some previous studies have shown that the traditional motion analysis clearly captured different strike patterns by observing the changes of pitch angle in different speed conditions [21, 22]. In addition, in order to find the optimal index of strike type that could represent the sensitivity in identifying different strike patterns (forefoot/heel strike) by using IMU, the cutoff value adjustments were repeated by each detected strike index value to identify the optimal cutoff value. The influence of the cutoff value points up the sensitivity of sensor fusion data that could represent the characteristics of strike patterns rather than using motion analysis system. The development of IMU device by using sensor fusion has been widely applied in diverse research area [12, 23, 24]. Liu et al. used their algorithm to process and integrate the signals from gyroscope and accelerometer by using mean filter and a Kalman filter to estimate the attitude angle of roll [25]. Their findings showed that the precision of estimating the angle of roll was improved effectively.

Based on the sensor fusion method using in this study, the sensitivity of detecting the heel strike pattern decreases with an increase in cutoff value leading to an increment of sensitivity to detect forefoot strike pattern. Thus, a directional effect of the cutoff adjustment is a function of whether forefoot or heel strike pattern is being measured. Using the cutoff value (0.115) in the intersection could not only precisely detect forefoot strike but also identify heel strike pattern very well as shown in Figure 5. Moreover, the effect of cutoff setting could correspond with the results showing that the correlation between the angle difference in IMU measurement and pitch angle of Vicon system was significantly high in sagittal plane. The comparison result of different devices showed that the data from the forefoot strike and heel strike were distributed along the identical line which meant that the signals recorded from these two systems were identical [25, 26]. In our case, although previous research used different algorithms to explore the effectiveness of sensor fusion methods, the optimal cutoff point set at IMU sensors has shown its utility in this study.

However, some limitations still exist in the index of strike type we used. For instance, the midfoot strike pattern in between forefoot and heel strike is not easy to distinguish. Besides, when IMU was attached to a different position, the result might also be different. In some other studies, the data collected from the axis orientations in the frontal and transverse planes were not identical between gyroscope and Vicon system [8]. Carmona et al. also pointed out that the weakness of their research of doing data fusion for drivers' behavior was that, for certain time interval, it is required to retrieve enough data to provide precise detection [26]. Furthermore, different people might need different threshold as a cutting point to determine the different strike patterns. Nevertheless, future studies may need to focus on the issues generated by the multifunctional nature of devices and simplify the data processing algorithm to find the suitable cutting point value [27, 28]. In this study, our index of strike type that defined cutoff value makes positive contributions to differentiate the strike patterns. The IMU device can not only identify different strike pattern with locomotion at different levels of intensity but also be considered feasible for the data collection outside of the laboratory because of being easy-to-carry and inexpensive [12, 29]. Based on our findings, the IMU sensors showed potential capabilities and this device could be extended beyond the context of sport science to other fields, including clinical applications.

Competing Interests

The authors declare that they have no competing interests.

Acknowledgments

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