Measuring kinematic changes of the foot using a gyro sensor during intense running

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Measuring kinematic changes of the foot using a gyro sensor during intense running

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Abstract
Gyro sensor has been used to measure foot pronation during running with reliable results in previous studies, and the signals were not affected by the vibration of heel strikes. The purpose of this study was to observe the kinematic changes of the foot during intense running using a 3-axis gyro sensor. Fifteen male participants (average age: 24.5 ± 1.7 years; mean height: 174.1 ± 3.3 cm; mean body weight: 71.0 ± 5.5 kg) were recruited in this study. Foot kinematic changes were observed in 30-min intense running protocols. The comparisons of the signals from gyro and motion analysis system were also performed to determine the accuracy of the gyro and showed positive results. In the main experiment, the ankle range of motion (ROM) in the frontal plane, measured using a motion system, showed a significant increase over time. Accordingly, peak angular velocity in the frontal plane also showed a significant increase. The correlation between ankle ROM and peak angular velocity in the frontal plane is significantly high (r = 0.975). Moreover, peak angular velocity in the frontal plane is also significantly correlated with both rate of perceived exertion (RPE) (r = 0.911) and heart rate (r = 0.960). This study concluded that an alarm system for foot kinematic changes related to running injuries can be built based on the peak angular velocity of the foot in the frontal plane.

Keywords: running, fatigue, pronated foot, 3D motion analysis system

Introduction
Wearable motion sensors have been considered as an inexpensive alternative to optical motion analysis systems for obtaining kinematic data (Mayagoitia, Nene, & Veltink, 2002). The optical motion analysis system has long been acknowledged to provide the precise human kinematic data, and the data from wearable motion sensors have been proven to be highly correlated with it (r = 0.9) (Liu, Inoue, & Shibata, 2009). Acceleration of human body segments and joint angular velocity can be measured by the digital sensors including accelerometers and gyro sensors. Comparing with the optical motion analysis systems, digital sensors can be developed to a fully portable system when the appropriate data logger is built in. Besides the low cost and portable characters, wearable motion sensors required less time to set up.

Wearable motion sensors were mostly used in lower extremity biomechanical studies (Schwesig, Leuchte, Fischer, Ullmann, & Kluttig, 2011; Yang, Mohr, & Li, 2011). Signals of lower extremities collected by digital sensors can be used to estimate physical activities, to monitor gait events and even to develop a sensor system for functional electrical stimulation (Butte, Ekelund, & Westerterp, 2012; Pappas et al., 2004; Takeda et al., 2009; Tong & Granat, 1999). The sensor was suggested to base on the footwear rather than shank to estimate sagittal plane, lower limb joint kinematics (Findlow, Goulermas, Nester, Howard, & Kenney, 2008). Also, a commercial product was produced from the accelerometer and set up in the mid-sole of the running shoe to record the running speed, distance and energy expenditure of the runners (Kane, Simmons, John, Thompson, & Basset, 2010). Digital sensor set on the footwear is a practical and useful tool to provide kinematics message and exercise information.

According to an epidemiological study, the yearly incidence rate of running injuries was 37–56% (van Mechelen, 1992). Moreover, 14.2% of injured runners required medication and 2.3% had to take time off from work (Marti, Vader, Minder, & Abelin, 1988). Because of repetitive characteristics, inappropriate movements of musculoskeletal tissues during running were considered to cause and accumulate injuries.
The risk factors of running injuries from the kinematic perspective include increased pronation excursion, prolonged eversion with a higher loading under the medial side of the foot and increased re-inversion velocity (Hintermann & Nigg, 1998; van Gheluwe & Madsen, 1997; Willems, Witvrouw, Cock, & Clercq, 2007). Based on the tri-plane motion of the subtalar joint, foot pronation occurs in combination with tibial internal rotation. Therefore, excessive pronation of the foot causes not only foot problems, but also affects knee and hip movements during running (Hintermann & Nigg, 1998). Researches have shown that some running injuries, such as plantar fasciitis, Achilles tendinitis, medial tibial stress syndrome, patellofemoral pain syndrome and iliotibial friction syndrome, are related to excessive pronation of the foot (Hintermann & Nigg, 1998; van Mechelen, 1992). Fatigue may also exacerbate the abnormal kinematic movements of running. Even minor deviations of movement at the beginning of running can cause an accumulation of trauma in the musculoskeletal system after thousands of steps (Cheung & Ng, 2007; Cheung, Wong, & Ng, 2011; McClay & Manal, 1998; Meardon, Hamill, & Derrick, 2011).

Although accelerometers have been applied in many commercial products and the price is relative low, the vibration of heel strikes will increase the errors and noises in acceleration signals, whereas the gyro sensors have not been thus affected (Brauner, Oriwol, Sterzing, & Milani, 2009; Ghoussayni, Catafamo, Moser, & Ewins, 2004; Mayagoitia et al., 2002). Therefore, gyro sensors are more suitable for detecting foot kinematic parameters, especially for those rotational variables. A single-axis gyro sensor set in the insole of a shoe was used to measure foot pronation during running, and the results proved the methods to be reliable (Brauner et al., 2009). However, the kinematic changes emphasis on foot pronation detected by 3-axis gyro sensor during intense, prolonged running has not been discussed in previous related studies. The feasibility of using gyro sensor for detecting the subtle variation of foot pronation during running has not been proved. The purpose of this study was to observe the foot kinematic changes during intense running using gyro sensor. Furthermore, the comparisons of the signals from gyro sensor and motion analysis system were also tested to ensure the accuracy of the gyro sensor used in this study.

Methods

Participants

Fifteen recreational runners were recruited in this study. The average age of the 15 participants was 24.5 ± 1.7 years; the mean height was 174.1 ± 3.3 cm; and the mean body weight was 71.0 ± 5.5 kg. All participants were healthy, without any musculoskeletal injuries of the lower extremities. The statistical power was 0.81 with effect size $f = 0.35$ which showed a nearly medium effect on outcomes. The study was approved by the Institutional Review Board of the Taipei Medical University and the written agreement consent of this study was signed by every participants.

Protocol and instrumentation

In the main experiment, participants ran on the belt treadmill (MAG-7310, Magtonic, Taiwan) for 30 min at 70% of their peak running velocity. The measurement of peak running velocity was based on the method proposed by Scott (Scott & Houmard, 1994). The kinematic data, heart rate and rate of perceived exertion (RPE) score were collected every 3 min. The average running speed during the 30-min run for all participants was $11.5 \pm 1.29$ km·h$^{-1}$.

A 3-axis gyro sensor was manufactured by 2 dual-axis gyro breakout boards (SEN-09412, SEN-09425, SparkFun, USA). The axis orientation of each board involved pitch/roll and pitch/yaw, respectively. Thus, the 3 axes were perpendicular to each other. The measurement range was ±1500 rad·s$^{-1}$, and the sensitivity was 0.67 mV·rad·s$^{-1}$. The data were collected and integrated in the Vicon MX (Vicon, Oxford, UK) control unit under an acquisition frequency of 1000 Hz. The gyro was fixed on the dorsal side of the shoe at the midpoint of the second metatarsal bone of left foot (Figure 1). Angular velocity of the foot was derived from the 3 axes of gyro sensor. Also, the change in the peak angular velocity during stance phase was observed in the main experiment during the 30-min running.

Figure 1. The settings of gyro sensor and foot markers. Arrows represent anterioposterior axis (Y) and superioinferior axis (Z) of Gyro.
A 3D motion analysis system (hardware model, Vicon; software model, Nexus 1.4, UK) was used to capture the motion data. The foot marker set was based on the Leardini foot model (Leardini et al., 2007) which assumed rigid segments of lower extremity including shank, calcaneus, mid-foot and metatarsus. Holes were cut on the shoe and sock at the site of the bony landmarks and the reflective markers of the motion system were stuck directly on the skin of the foot. No cluster was used in this marker set. The angles were created using Euler technique, and the sequence of rotation was XYZ which has been proved to have the minimal crosstalk for calculating frontal/transverse plane kinematics from sagittal plane (Sinclair, Taylor, Edmundson, Brooks, & Hobbs, 2012). Visual 3D™ (C-Motion Inc., Germantown, USA) was used to calculate the kinematic data including angular velocity of the metatarsal and ankle range of motion (ROM). The angular velocity of the metatarsal segment measured using the motion analysis system was the established gold standard for the comparison with the signal from gyro sensor. The ankle ROM was defined as the angle of shank and calcaneus during the stance phase throughout the 30-min running protocol. The heel strike and toe off were defined by the lowest position of the heel and toe markers (Jordan, Challis, Cusumano, & Newell, 2009; Novacheck, 1998; Sajko & Pierrynowski, 2005). Other devices, including a heart rate monitor (Polar, USA) and a Borg scale for RPE, were used to measure the activity level of the participants during the running protocol.

The comparison of the signals from gyro sensor and motion analysis system was both tested in the beginning and in the end of the 30-min running protocol. The correlation coefficients of angular velocity of the metatarsal segment measured by gyro sensor and Vicon system in 3 anatomical planes were calculated. Another correlation test was performed to examine the correlation between peak angular velocity and ankle ROM during the 30-min running protocol.

**Statistical analysis**

The correlation coefficient and the normalised root mean square error were calculated to compare the data collected using the gyro and Vicon. In the main experiment, running data were collected every 3 min from the beginning to the end of the 30-min fatigue protocol. Time was the main effect tested, using a one-way repeated measures ANOVA. When a main effect was detected, Bonferroni post hoc analysis was used. The alpha level was set at 0.05.

**Results**

**The comparison of the signals from gyro sensor and motion analysis system**

The angular velocity of metatarsal segment during running exhibited a high correlation between the gyro and Vicon signal in the sagittal plane \(r = 0.973\) and a moderate correlation in the frontal \(r = 0.651\) and transverse planes \(r = 0.611\). The normalised root mean square errors of gyro and Vicon signal in sagittal, frontal and transverse plane were 0.29, 0.79 and 0.98. After 30 min of running, the results remained nearly the same, the correlation coefficients in sagittal, frontal and transverse plane were 0.974, 0.699 and 0.584, respectively. The normalised root mean square errors of gyro and Vicon signal after 30 min of running in sagittal, frontal and transverse plane were 0.24, 0.73 and 1.03.

**Main experiment**

During 30-min running periods, participants showed constant and significant increases in activity level in both heart rate and the RPE scale (Figure 2(a), (b)). The ankle ROM measured using the Vicon in the frontal plane and peak angular velocity measured using the gyro in the frontal plane also showed constant and significant increases (Figure 2(d), (g)). Other variables, including the ankle ROM in the sagittal and transverse planes, as well as the peak angular velocity in the sagittal and transverse planes, did not show significant variation during 30-min running (Figure 2(c), (e), (f), (h)). The significant increase can be further determined according to the one-way ANOVA test result. Ankle ROM and peak angular velocity in the frontal plane showed significant differences between the beginning and middle, as well as the middle and end of the running protocol (Table I).

The correlation between peak angular velocity and ankle ROM are high in the frontal plane \(r = 0.975\), whereas only a low-to-middle correlation is in the other 2 planes \((r = 0.365 – 0.647)\). The correlations between peak angular velocity and RPE or heart rate are also showed highly correlated in the frontal plane \((r = 0.911 – 0.960)\) (Table II). The variation trends of ankle ROM and peak angular velocity in the frontal plane during the 30-min running periods were highly similar (Figure 3).

**Discussion**

The purpose of this study was to measure the kinematic changes of the foot during intense running using a 3-axis gyro sensor. Also, the comparisons of the signals from gyro sensor and motion analysis...
system were tested to ensure the accuracy of the gyro sensor used in this study. The result of the correlation between gyro and Vicon signal in the sagittal plane was very high and similar with a previous study ($r = 0.90 – 0.94$) (Tong & Granat, 1999). However, the axis orientations in the frontal and transverse planes were not identical between gyro sensor and motional analysis system. The axis orientations in the motion analysis system were determined according to the reflective markers, which was stuck on the bony landmarks of the foot; whereas the axis

Table I. The heart rate, RPE and kinematic data measured using the Vicon (ankle ROM) and gyro (peak angular velocity) during the 30-min running. The values in the table showed mean value and standard deviation of the 15 participants.

<table>
<thead>
<tr>
<th></th>
<th>Begin</th>
<th>Middle</th>
<th>End</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate (bpm)</td>
<td>149.5 ± 16.6</td>
<td>173.3 ± 12.4*</td>
<td>181.8 ± 14.2**</td>
</tr>
<tr>
<td>RPE scale</td>
<td>11.9 ± 1.0</td>
<td>15.4 ± 1.2*</td>
<td>17.3 ± 2.1**</td>
</tr>
<tr>
<td>Ankle ROM_Sagittal (°)</td>
<td>22.1 ± 4.5</td>
<td>22.6 ± 4.8</td>
<td>23.0 ± 4.9</td>
</tr>
<tr>
<td>Ankle ROM_Frontal (°)</td>
<td>11.7 ± 3.3</td>
<td>13.5 ± 3.6*</td>
<td>14.2 ± 3.8**</td>
</tr>
<tr>
<td>Ankle ROM_Transvers (°)</td>
<td>4.1 ± 2.0</td>
<td>4.4 ± 2.1</td>
<td>4.7 ± 2.6</td>
</tr>
<tr>
<td>Peak angular velocity_Sagittal (° · s$^{-1}$)</td>
<td>$–21.6 ± 38.6$</td>
<td>$–5.4 ± 48.8*$</td>
<td>$–7.2 ± 32.4$</td>
</tr>
<tr>
<td>Peak angular velocity_Sagittal (° · s$^{-1}$)</td>
<td>$428.7 ± 108.1$</td>
<td>$474.7 ± 91.0*$</td>
<td>$494.8 ± 109.8*$</td>
</tr>
<tr>
<td>Peak angular velocity_Sagittal (° · s$^{-1}$)</td>
<td>$284.1 ± 97.6$</td>
<td>$302.8 ± 85.9$</td>
<td>$309.6 ± 88.9*$</td>
</tr>
</tbody>
</table>

Notes: *Significant difference compared to the value of the beginning condition ($P < 0.05$).
#Significant difference compared to the value of the middle condition ($P < 0.05$).

Table II. Correlations between peak angular velocity of the foot and ankle ROM, RPE, as well as heart rate during 30-min running periods in 3 planes.

<table>
<thead>
<tr>
<th>Correlation coefficient</th>
<th>Sagittal plane</th>
<th>Frontal plane</th>
<th>Transverse plane</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ankle ROM</td>
<td>0.365</td>
<td>0.975*</td>
<td>0.647*</td>
</tr>
<tr>
<td>RPE</td>
<td>0.681*</td>
<td>0.911*</td>
<td>0.712*</td>
</tr>
<tr>
<td>Heart rate</td>
<td>0.598</td>
<td>0.960*</td>
<td>0.825*</td>
</tr>
</tbody>
</table>

Note: *$P < 0.05$. 

Figure 2. Heart rate, RPE ankle ROM (measured using the Vicon) and peak angular velocity of the foot (measured using the gyro) during 30-min running periods.
orientations of the gyro sensor were determined according to the axes of the printed circuit board, which was stuck on the dorsal side of the shoe. This could explain the only moderate correlation in the frontal and transverse planes. In addition, a previous study also showed a similar correlation \((r = 0.61 \pm 0.73)\) in the frontal plane using gyro signal (Brauner, Sterzing, & Milani, 2009).

To examine the feasibility of using gyro sensor to measure the kinematic changes of the foot during intense running, a protocol of high-intensity running was used. The heart rate and RPE scale both indicated a “very hard” status at the end, rather than a “fairly light” status at the beginning of the running protocol (Borg, 1998). To observe the foot pronation, the fatigue protocols used in other studies were either to produce cardiopulmonary exhaustion or local muscle fatigue (Cheung & Ng, 2007; Christina, White, & Gilchrist, 2001; Dierks, Davis, & Hamill, 2010; Hamill, Freedson, Boda, & Reichsman, 1988; van Geluwe & Madsen, 1997). In order to simulate the fatigue condition after intensive running and to normalise the intensity of the running protocol among every participant, percentage of peak running velocity was used in this study (Scott & Houmard, 1994).

Previous studies have intensely discussed the kinematic changes after prolonged running to determine the relationship between these kinematic changes and running injuries (Cheung & Ng, 2007; Dierks et al., 2010; van Geluwe & Madsen, 1997). Excessive pronation of the foot was thought to be one of the main risk factors of running injuries (van Geluwe & Madsen, 1997). In this study, the kinematic changes of the foot measured from Vicon occurred in ankle ROM which was expected and was agree with previous studies (Cheung & Ng, 2007; Dierks et al., 2010; van Geluwe & Madsen, 1997). Although the kinematic changes after fatigued running involved across the joints of the entire lower extremity (DeLeo, Dierks, Ferber, & Davis, 2004; McClay, 2000), the greatest inference was occurred at the foot–ground interface and the rear-foot eversion was influenced the most by the level of exertion (Dierks et al., 2010).

In the gyro data, the peak angular velocity in the frontal plane in the frontal plane also increased significantly over time. Other axes of gyro signals did not show the same trends at the same time. The higher pronation velocity was addressed to be a risk factor for stress fractures (Hetsroni et al., 2008). Also, the peak angular velocity of eversion showed significant increase in an exerted state running (Dierks et al., 2010). The gyro in this study was not setting at the rear foot where most of the previous studies did, however, the correlation between the peak angular velocity of gyro and ankle ROM of Vicon was significantly high in frontal plane \((r = 0.975)\). Therefore, as a monitor for increasing ankle ROM in frontal plane, the gyro sensor set at forefoot showed its utility in this study.

The application of a gyro sensor placed on the foot to prevent running injuries has yet to be determined; but the results of this study can be a valuable reference for running fatigue detection. Many scientists believe that humans tend to change running gait to conserve energy, rather than reduce shock impact on musculoskeletal tissue (Hamill, Derrick, & Holt, 1995; Hardin, Van Den Bogert, & Hamill, 2004). Therefore, monitoring fatigue-induced running gait change is critical in preventing running injuries. For future studies, investigating ground reaction force and electromyography are suggested to gain more information about running injuries and muscle fatigue. According to our results, only the frontal plane signal exhibits a highly correlated change with ankle movement; therefore, only a single-axis gyro sensor is required for future application.

Digital kinematic devices were considered feasible for the field study because of being light, portable and inexpensive (Picerno, Camomilla, & Capranica, 2011). Based on our results, the peak angular velocity in the frontal plane can reveal the changes of the ankle frontal plane ROM during 30-min periods of intense running. Therefore, a running fatigue alarm system for preventing pronated foot-related running injuries can be developed based on the gyro signal.

**Conclusion**

In this study, signals from a 3-axis gyro sensor are highly correlated with the 3D motion analysis system when the axis orientations are identical. In addition, a gyro sensor can be used to detect the kinematic changes in the front plane of the foot during prolonged running, which has been proved to be a risk factor of running injuries. Furthermore, an alarm...
system for pronated foot-related running injuries can be developed based on the peak angular velocity of the foot in the frontal plane.

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**References**


