

A WEARABLE FOOT MOTION TRACKING SENSOR FOR OUTDOOR RUNNING

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Throughout human history, running has evolved from a form of locomotion to a recreation or competitive pursuit. The purpose of this project was to develop a foot motion tracking sensor using inertial measurement unit (IMU) to determine the running kinematics of the ankles of individuals under different external or physical conditions such as change in directions, running on slopes or level ground or fatigue. These results may be helpful in providing a real-time quantitative data, which will be useful for runners to monitor their training programs and routes. The preliminary results showed that the system can detect ankle dorsiflexion/plantarflexion across different route condition, where these results can be used for further analysis such as designing a training program and monitoring the fatigue level.

KEY WORDS: outdoor running, foot, dorsiflexion, plantarflexion, fatigue.

INTRODUCTION: Throughout human history, running has evolved from a form of locomotion to a recreation or competitive pursuit. Currently, running has been linked to good health and longevity. According to the studying done by Lee *et al.* from Iowa State University, runners has a 30% lower risk of death from all causes and 45% lower risk from heart diseases or stroke compared to non-runners (Lee et al., 2014). However, the occurrence of injury sustained in the lower extremity during running has been reported to range from 20% to 79% (Van Gent et al., 2007). Due to the high injury risks and health benefits of running, great interest has been garnered into the biomechanics of running. For example, the 'minimalist' running concept introduced by Liberman *et al.* (2010) has provided debate among many researchers. Liberman *et al.* proposed that running in minimal footwear or barefoot will reduce injury risks and improve performance due to altered foot strike pattern to forefoot strike. The absence of a distinct peak impact force in forefoot strikers is linked to the reduced injury risks. However, Jenkins and Cauthon (2011) and Lorenz & Pontillo (2012) believed that there is insufficient evidence to support claims of a positive effect of barefoot running. Moreover, runners are gaining interest in having their running data collected to monitor their workout and improve their running efficacy.

Currently, multiple types of gait sensors have been developed to cater to both researchers and runners alike. Some examples of gait sensors include RunScribe and Nike+sensor. RunScribe is a lightweight, wearable sensor developed by Tim Clark and John Litschert to be mounted at the back of the shoe to detect the kinematics of the foot during gait cycle. It records foot kinematics data using a 9-axis sensor, capturing kinematics metrics such as pace, distance, strike rate and length, contact time, type of strike pattern. Nike+Sensor is a wearable sensor that can be placed under the sock liner of the shoe to measure kinematics data such as pace, distance, time lapsed and calories burnt. It has a more limited range of kinematics metrics as compared to RunScribe. The project aimed to develop a foot motion tracking sensor using inertial measurement unit (IMU) to determine the running kinematics of the ankles of individuals under different external or physical conditions, such as change in directions, running on slopes or level ground or fatigue. These results may be helpful in providing a real-time quantitative data which will be useful for runners to monitor their training programs and routes, as well as reducing the risks of running injuries and improve running efficiency of runner in the future.

METHODS: 10 healthy young subjects (5 male & 5 female, BMI: $20.7 \pm 1.75 \text{ kg/m}^2$ with no previous history of joint injuries or deformities were recruited from the local university. Each participant was required to run a distance of approximately 1.72km on a route that comprises of several characteristics; upslope, downslope, straight path and changes in direction. The subject will stop at a checkpoint and run the same route back to the starting point to evaluate the effect of fatigue. The prototype (Figure 1) which consists of an IMU sensor (Pololu MiniIMU-9 v3) , Arduino (Arduino Pro Mini), battery (Polymer Li-ion battery) and wireless transmitter XBee Pro (Digikey, USA), placed in a casing, was secured on the subject's running shoe on dominant leg for data collection. The weight of the IMU sensor, casing and battery is measured to be 45g. The same model of running shoes (Power, BATA) was used for all the trials. Subjects' ankle kinematics was captured by the foot motion tracking sensor and the data was transmitted to a laptop at a baudrate of 115200 bps. All the participants were required to perform warm up exercises for 5 to 10 minutes prior to the experiment to reduce the risk of injuries. The warm up exercises comprises of hamstring stretches, quadriceps stretches, calf stretches and slow jogging with high knees. They were then tasked to run along the route predetermined for them at their own pace. The starting point of the route was a straight path (route section 1 and 12). Upon seeing the sign, the subjects turned right and ran upslope (route section 2 and 11), cross a short distance of the road and continue upslope to the peak checkpoint (route section 3 and 10) and took a turn back downslope to the main road (route section 4 and 9). The subject continued on a straight path to a bus stop (route section 5 and 8). Upon reaching the bus stop, the subject turned right and continued running until they reached the checkpoint (route section 6 and 7). They took a U-turn and ran the same way back to the starting point. Timings were noted down at several checkpoints placed along the route to determine the effect of running terrain or fatigue condition on speed and ankle kinematics. Plantar-flexion/dorsi-flexion angles were compared between running on level ground (L1) and upslope (L2) as well as for running on level ground between outbound and inbound route for L5 and L8. The difference of ankle kinematics across gender will also be studied.

All kinematics data (ankle joint angles) were averaged among all subjects. Paired and unpaired t-tests were used to compare the biomechanics parameters for different sections of the route between terrains and genders respectively.

RESULTS: The results showed that there is no significant difference in both foot dorsiflexion and plantarflexion between running on level ground (L1) and upslope (L2). The comparison of maximum dorsiflexion angles for the same section of route on level ground between inbound and outbound route showed that there is a significant decrease (17.73%, $p=0.01$) in the maximum dorsiflexion angles obtained by the subjects when running on the inbound route (L8) as compared to the outbound route (L5) (Figure 2). However, there was no significant difference for maximum plantarflexion angles observed among the subjects between outbound and inbound route.

Moreover, the female subjects showed a higher mean maximum plantar flexion angles in all routes as compared to male subjects and with significant difference especially at section route 1, 3, 7, 8, 9, 11 (Table 1). However, there was no significant difference ($p<0.05$) in mean maximum dorsiflexion across gender which means that the female subjects tend to have larger foot range of motion throughout the entire running.

The polar graph for the internal/external rotation of the angle against time showed that changes in direction can be detected by the change in rotation of the ankle during the transition of Section 1 to 2 and Section 2 to 3. A right turn was made by the runners upon transitioning from Section 1 to 2 of the route, which can be observed by the 358° to 60° change in ankle rotation (denoted by A in Figure 3). This was further supported by the transition from Section 2 to 3 of the route, where the subject made a turn at the crossing of

the road and to continue running in approximately the same direction as in section 1, which can be observed by the 92° to 355° change in ankle rotation (denoted by C in Figure 3).

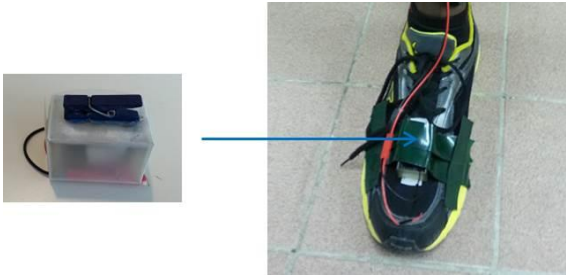


Figure 1: Sensor prototype attached onto the running shoe.

Table 1
Significant difference in mean peak foot plantarflexion (standard deviation) across gender.

Route Section	Male	Female	p-value
1	47.48(14.25)°	67.73(7.13)°	0.02
3	60.05(1.32)°	67.3(6.91)°	0.04
7	60.83(2.16)°	67.99(4.45)°	0.01
8	61.39(2.16)°	71.13(3.46)°	0.001
9	61.75(1.98)°	71.57(3.71)°	0.002
11	58.32(2.99)°	69.13(5.99)°	0.009

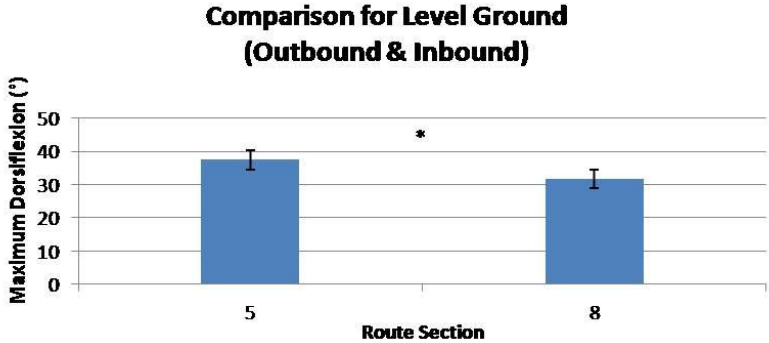


Figure 2: Comparison of foot dorsiflexion for level ground for outbound (section 5) and inbound route (section 8). * Significant difference at p<0.05.

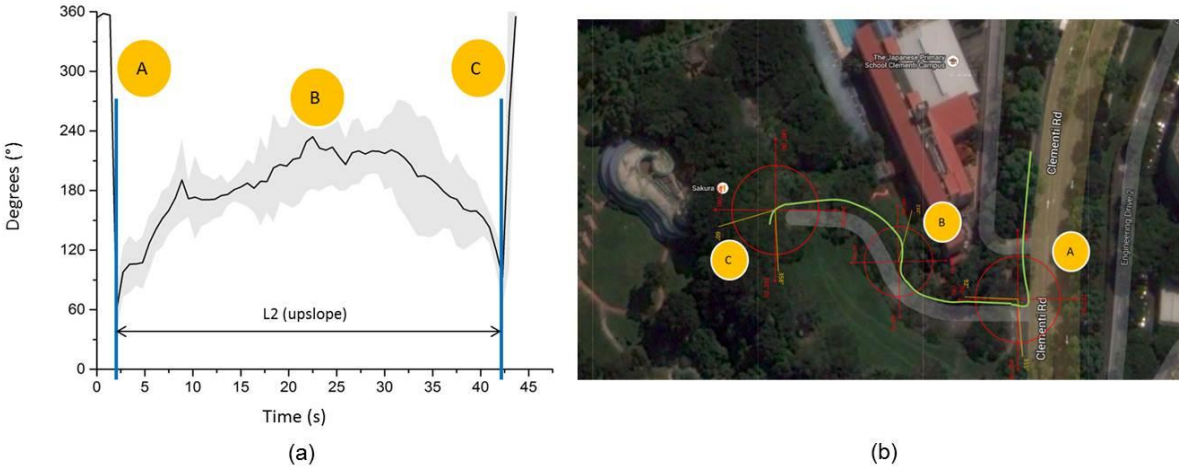


Figure 3: (a) Polar graph of internal/external rotation of foot against time; (b) The top view of map for section route 2 and the transition from 1 to 2 and 2 to 3.

DISCUSSION:

In the comparison for route section 5 and 8 (level ground for outbound and inbound route respectively), the decrease in foot dorsiflexion angles when running the inbound route might be due to muscle fatigue experienced by the runners as most runners stated feeling fatigue on their questionnaire at around this region of the route. Hence the subjects were less inclined to do more work in the foot flexion during running due to being tired. This was supported by the smaller range of motion observed for foot plantar/dorsiflexion in the inbound route than outbound route. Moreover, a study done by Kellis & Liassou (2009) on 15 females running at 3.61m/s on a treadmill (level ground) found that ankle muscle fatigue causes decreased in ankle dorsiflexion (Kellis & Liassou, 2009), which support the above observation.

Moreover, females are found to have a significant difference in dorsiflexion during running as compared to the males. This might be due to the differences in skeletal structure between genders. Sepic et al. (1986) have shown that plantar flexion and range of motion of the ankle are greater in women, possibly due to greater laxity in female ligaments. Studies have also observed greater ankle and knee laxity values in women. Our results are consistent with their studies in which that the foot plantarflexion was significantly higher in female as compared to male. Lastly, the foot external-internal rotation data showed that the changes in direction can be determined by the foot motion tracking sensor. A right turn will result in an external rotation of the right foot and a left turn will result in an internal rotation of the right foot.

CONCLUSION: This study has developed a foot motion tracking sensor which can detect foot dorsiflexion-plantarflexion and external-internal rotation during outdoor running. The foot kinematics obtained from the sensor can be used to relate to the fatigue, detection of running on level ground or slopes and changes in directions as well as the differences in plantarflexion across male and female subjects. This study demonstrated the possibility to integrate this system with a mobile application to establish a detailed foot motion tracking system which can be used for monitoring of long distance running.

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