33rd Annual International Conference of the IEEE EMBS
Boston, Massachusetts USA, August 30 - September 3, 2011

Using a tri-axial accelerometer to detect technique breakdown due to fatigue in distance runners: a preliminary perspective

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***Abstract*— Accelerometer technology is becoming increasingly smaller and cheaper to develop. As a direct result, such devices can potentially be easily integrated into footwear to capture data that provides information about the quality of a person's running technique in the later stages of a fatiguing run. The purpose of this study is to determine if it is possible to detect technique breakdown due to fatigue in a distance runner using shoe mounted accelerometers. We present an algorithm that uses computationally light data from tri-axial foot mounted accelerometers and compares outputs from them to kinematic changes in the runner as the runner fatigues. These preliminary findings show that kinematic changes due to fatigue can be reasonably estimated using outputs from a shoe mounted tri-axial accelerometer.**

I. Introduction

Fatigue in distance running often results in technique breakdown which in turn can result in decreased running economy and possible injury risk. Technique assessment of running has been traditionally confined to complex biomechanics laboratories utilizing motion capture systems and force plates [1]. With the current popularity of endurance running, ubiquitous technique monitoring could be helpful in preventing injuries and improving performance. Previous research towards ubiquitous analysis of running gait has utilized a variety of sensors, such as in-sole pressure sensors, accelerometers, gyroscopes and electogoniometers [1].

Previous research has examined differences in lower-limb kinematics and spatio-temporal parameters in runners due to fatigue and has reported a variety of changes in running technique. Mizrahi et al in 2000 found that fatigued runners exhibited a decreased stride rate, increased ankle angle at maximal knee flexion, a decreased average knee flexion from foot strike (FS) and increased impact accelerations at (FS) [2]. Williams et al in 1991 found that, overall, runners exhibited an increased step length, increased maximal knee flexion during swing and an increased thigh angle during hip flexion when in a fatigued state. However, they concluded that the spread of the kinematic changes across all of their subjects was too great to generalize the findings to every runner [3]. This research suggests that technique breakdown in distance running is individual for each athlete.

Much of the research on using accelerometers to analyze running performance has utilized a lumbar mounted accelerometer. Lee et al in 2010 used a lumbar mounted inertial sensor to measure vertical acceleration in running in order to detect asymmetry and changes in running velocity [4]. Le Bris et al in 2006 used a tri-axial accelerometer mounted at the low back to measure lateral movement and temporal-spatial periodicity of the running cycle. They found that these variables were altered in the presence of fatigue in runners [5].

A more ubiquitous method of measuring running performance would be to embed accelerometers in running shoes and have them communicate wirelessly with a local smart-phone or music device. Much sensor research utilizes accelerometers combined with gyroscopes, termed inertial measurement units (IMU's). Using only accelerometers is cheaper, smaller and requires less processing capacity; all relevant considerations when implementing practical methods of ubiquitous technique monitoring in athletes. Commercial systems are available in which shoe embedded sensors communicate wirelessly with a local mobile device, however they are limited to measurement of spatio-temporal data for the purposes of assessment of pace or distance covered. They do not provide any detailed information regarding running technique.

Outputs from a shoe embedded sensor that could detect important kinematic changes as a runner fatigues could be used to warn an athlete when their technique is breaking down. This would be useful in preventing injuries and ensuring athletes do not develop poor motor patterns by training with poor technique.

The aim of this study was to investigate the relationships that exist between changes in foot mounted tri-axial accelerometer outputs and lower limb joint kinematics as a runner fatigues in order to investigate the feasibility of using accelerometers to identify technique breakdown that occurs with the onset of fatigue.

II. Methods

One top level recreational runner (marathon time 2hr 51min) performed a fatigue protocol on a treadmill. The athlete performed a ten minute light running warm up at a self-selected pace, followed by a further five minute period of running with the goal of progressively increasing the speed to a pre-defined *steady-state* pace. The steady-state pace was defined as 1km/h above the athlete's 10km race

Manuscript received April 15th 2011. This work was supported by Science Foundation Ireland under grant 07/CE/I1147.

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pace. The steady state speed for this athlete was 17 km/h. The data collection began with a ten minute period of steady-state running (SS1), followed by five fatiguing high intensity 45s intervals, each separated by 1-minute of recovery running. This was followed by a second period of steady-state running (SS2) for ten minutes. The interval speed was 20 km/h and the recovery speed between intervals was 12 km/h. A ten minute cool down at a self selected pace was performed at the end of the protocol. Figure 1 illustrates the protocol.

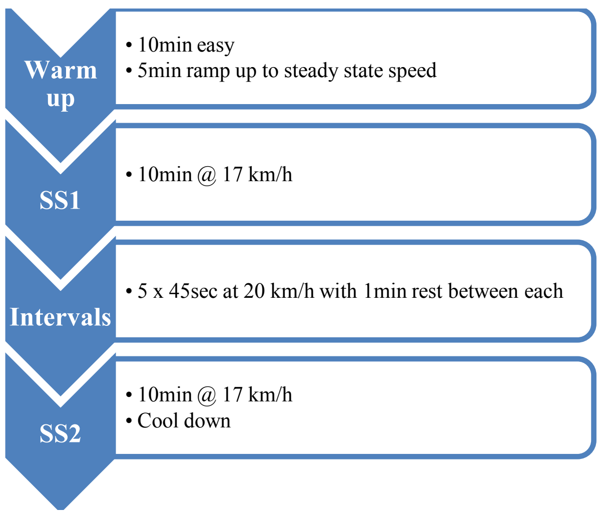

Fig. 1. Fatigue protocol

A CODA motion capture system (Leicestershire, UK) was used to collect kinematic data. Markers were placed on the participants right and left sides at PSIS', ASIS', greater trochanters, femoral condyles, fibular heads, lateral malleoli, heels, toes, inferior calcaneous' and superior calcaneous'. An Xsens MTx IMU (Enschede, Netherlands) was placed on top of each subjects shoe above the shoe laces, they were held in place with athletic tape.

Kinematic data was collected for a 20 second block during each minute for the steady state running periods. Synchronous Xsens IMU information was analysed for the same time periods and the average factors for each 20 second block were used to compare the IMU data to the kinematic data.

Acceleration data was analysed in MATLAB 2009b (Natick, Massachusetts). Total acceleration (TA) was calculated from x, y and z acceleration signals by using equation 1.

$$\textit{Total acceleration (TA)} = sqrt(Ax^2+Ay^2+Az^2) \qquad (1)$$

Total acceleration, y-acceleration and x-accelerations were used to quantify the acceleration data. Y-acceleration represents the vertical acceleration while the athlete was standing still with the sensor mounted on the dorsum of his foot. X-acceleration represents the anterior-posterior direction. Upwards and forwards represent the positive direction for the Y and X axes respectively.

An algorithm was created to quantify variables from the accelerometer data. It worked by first finding the fundamental frequency of TA and then TA was band pass filtered between 0.3 Hz to half of the fundamental frequency. On the sinusoidal resultant curve, minimum values were used to estimate roughly where initial swing occurred and the halfway point between each maximum to minimum value was used to estimate where FS occurred. Peak initial swing values were then search for around the minimum value from the band pass filtered TA curve. FS was determined by searching for the peak z-acceleration value around the estimated FS point.

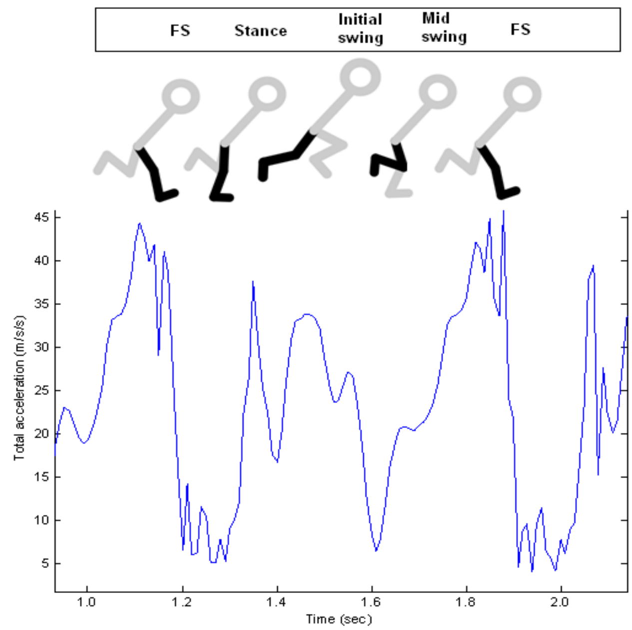

Fig. 2. Total acceleration during the running cycle

Figure 2 shows TA for a complete stride cycle. FS is associated with a sharp spike on the TA curve followed by a sharp decline to low TA values. Ground contact is associated with a short period of lower acceleration values, which is then followed by a sharp rise in TA during initial swing. The peak TA during initial swing was quantified as well as the peak y and x-acceleration values during this phase. During mid swing the total acceleration rises and dips. The average TA during mid-swing was quantified as well as the minimum y-acceleration value. TA rises sharply again at terminal swing before FS.

III. Results

A summary of main kinematic markers of technique breakdown is illustrated in Table 1, which outlines averaged values for each variable calculated over multiple cycles (>150 in SS1 and >90 in SS2) during the first and second steady state conditions. Patterns of changes were not symmetrical on left and right for each variable. Changes ranged from the very modest 1.5-1.7% average change of maximum hip flexion angular displacement during swing to the relatively large 17-31% change in maximum knee extension prior to foot strike. Relationships between selected kinematic variables and accelerometer derived variables are illustrated in Table 2. Moderate to strong relationships were observed across a large range of variables.

TABLE I
CHANGES IN KINEMATIC VARIABLES DUE TO FATIGUE FROM STEADY STATE ONE TO STEADY STATE TWO

	R Leg	L Leg
Max ankle dorsiflexion angular velocity before FS (◦/s)	-0.5 (5%)	-1.7 (19%)
Max hip flexion during swing (◦)	+1.0 (1.5%)	-1.1 (1.7%)
Max hip extension after TO (◦)	+0.8 (6.3%)	-0.4 (4.9%)
Max knee extension before FS (◦)	+1.0 (17%)	+2.1 (31%)
Max ankle plantarflexion angular velocity after FS (◦/s)	-0.1 (1%)	-0.7 (12%)

IV. Discussion

A. *Kinematic changes*

The athlete in this study showed signs of technique breakdown in the second steady state condition. Maximum ankle dorsiflexion angular velocity decreased on both feet in the fatigued condition; though the decrease was more pronounced on the left foot (19% vs 5% change). A similar discrepancy between left and right was observed for maximum ankle plantar-flexion angular velocity after FS, which remained stable on the right but decreased by 12% on the left. In general, it is evident that this athlete developed a more asymmetrical running style in the fatigued condition; maximum hip flexion during swing increased on the right side but decreased on the left side, and maximum hip extension after toe-off (TO) increased on his right side but decreased on his left side. His maximal knee extension before FS increased on both right and left sides, but the increase was greater on his right side.

B. *Initial swing variables*

Acceleration peaks at initial swing were related to several hip, knee and ankle kinematic factors from stance to terminal swing. Peak TA at initial swing was related to the knee angle at TO as well as the maximal hip flexion during swing.

An increase in knee flexion resulted in higher TA peaks during initial swing as the foot was moved closer to the hip to decrease the moment of inertia of the leg for swing. Hip flexion angle during terminal swing increased on the right side and decreased on the left side during the fatigued condition. This may be indicative of a right hip extensor fatigue in this subject. The right hip extensors could not initiate as strong a hip extensor moment at TO resulting in a lower peak TA during initial swing and could not slow down the hip from flexing beyond the optimal flexion range at terminal swing.

TABLE I
PEARSON CORRELATION COEFFICIENTS TO DESCRIBE RELATIONSHIPS BETWEEN VARIABLES MEASURED USING ACCELEROMETERS AND CODA MOTION CAPTURE SYSTEM

Accelerometer Derived Variable	CODA Derived Variable	Pearson R foot	Pearson L foot
Peak TA initial swing	Knee angle @ peak TA post TO	-0.52	-0.81
	Max hip flex during swing	-0.60	-0.74
Peak Ay initial swing	Max hip flex during swing	-0.66	-0.69
	Max hip ext around TO		
	Max ankle dorsif stance	0.92	0.55
		-0.75	-0.45
Peak Ax initial swing	Knee angle @ peak TA post TO	0.71	0.83
	Max hip ext around TO	-0.68	-0.53
	Max knee ext ang vel stance	-0.42	-0.61
Mean TA mid-swing	Ankle angle @ FS	0.72	0.58
	Max ankle dorsif ang vel b4 FS	-0.74	-0.51
	Max ankle plantar ang vel after FS	0.66	0.47
Min Ay mid-swing	Ankle angle @ FS	0.55	0.58
	Max ankle dorsif ang vel b4 FS	-0.63	-0.62
	Max ankle plantar ang vel after FS	0.48	0.61
	Max knee ext b4 FS	-0.43	-0.60

Most of the acceleration at initial swing occurs in the x and y planes of the sensor, thus the y and x acceleration peaks have a close relationship to the peak TA at initial swing. However, y and x acceleration peaks were each related to different kinematic variables. Lower peak y-acceleration values during initial swing were associated with a larger peak hip flexion angle during terminal swing; showing a similar relationship as peak TA during initial swing. A lower hip extension angle during initial swing resulted in higher acceleration levels in the y-plane, possibly because the hip extension had to decelerate much quicker since it was not being extended as far. Higher maximal ankle dorsi-flexion angles during stance are also associated with a lower peak y-acceleration during initial swing. Maximal ankle dorsi-flexion during stance increased in the fatigued steady state condition. These two factors are potentially related because ankle plantar-flexor fatigue may have resulted in poor ankle control during stance, causing increased level of dorsi-flexion during mid-stance as well as a weaker TO during terminal stance.

Peak x-acceleration during initial swing was also associated with maximum hip extension post TO. The Peak x-acceleration during initial swing was associated with knee movement during initial swing and stance. A higher peak x-acceleration during initial swing was associated with a lower knee angle at TO possibly because the knee had a shorter period of time to slow down flexion and thus greater levels of deceleration were experienced at the foot. Higher max knee extension angular velocity during stance resulted in a more powerful TO and was seen by an increase in peak Ax during initial swing.

Initial swing variables from the accelerometer data seem to be indicative of hip extensor fatigue and poor ankle control during stance due to plantar-flexor fatigue for this athlete.

C. *Mid-swing variables*

Accelerometer variables during mid-swing were associated with knee and ankle kinematic data around FS. Increased dorsi-flexion at FS was associated with lower mean TA values during mid-swing. Lower mean TA during mid-swing was associated with higher maximal ankle dorsi-flexion angular velocity before FS and with higher maximal ankle plantar-flexion angular velocity after FS.

Maximum ankle dorsi flexion angular velocity before FS and maximum ankle plantar-flexion angular velocity after FS both decreased in the fatigued condition, likely showing a dorsi-flexor musculature fatigue concentrically and eccentrically. The increase in mean TA during swing shows that this dorsi-flexor fatigue was associated with a less constant velocity and higher acceleration during mid-swing; though the cause of changes in the acceleration swing data is more likely tied to fatigue in other locations. However this athletes fatigue patterns seems to include decreased dorsi flexor control, so perhaps detection of that can be used to signal an altered running pattern.

Minimum z-acceleration during mid-swing is associated with a more steady velocity of the leg during this phase. Minimum z-acceleration during mid-swing was associated with the same ankle kinematic data as mean TA during mid-swing; however it was also associated with maximal knee extension before foot strike. Increased minimum z-acceleration levels at mid-swing are related with increased knee extension angles before FS.

Knee extension angle before FS increased on both legs in the fatigued condition and was detected by an increased minimum z-acceleration during mid-swing. Both factors suggest a knee flexor fatigue. The knee flexors may not be able to hold the knee angle in a smooth manner throughout swing resulting in an increased acceleration. In terminal swing the knee flexors may not be able to work optimally to eccentrically prevent the knee from extending beyond its optimal range of motion, resulting in increased knee extension before FS.

For the athlete in this study there is a strong relationship between acceleration variables at the foot during mid-swing and lower limb kinematics around FS. It seems that for this athlete having lower levels of mean TA and a lower minimum z-acceleration during mid-swing result in a better running technique. This means that the runner was moving their swing leg in a less smooth motion during the fatigued condition, which was related to a decrease in angular velocities around the ankle at FS and the knee extending beyond its optimal range of motion before FS.

For this athlete accelerometer variables during initial swing were predictive of ankle plantar flexor and hip extensor fatigue. Accelerometer variables during mid swing were predictive of dorsi-flexor and knee extensor fatigue.

V. Practical Considerations

Accelerations were kept in a local orientation in relation to the sensor. It was envisaged that this would increase the usability of these variables in a real world setting, since they do not rely on computationally heavy acceleration re-orientation into a global state. This is an important consideration for a system such as this to function in the real world as there is limited battery life and processing capacity on board the sensors themselves and the mobile devices that would be collecting the data.

This test was carried out on a treadmill. However, acceleration profiles during treadmill running are likely to be slightly different than over-ground running. The main difference expected is the sharp rise in TA during terminal swing due to deceleration of the foot in treadmill running; this is unlikely to be observed in over-ground running as the athlete would be moving forward.

The accelerometer variables in this study were processed off-line. For such variables to be useful to an athlete, near real-time feedback would be necessary to alert the athlete that their technique is beginning to break down. Twenty second periods of running were processed in this study. A similar period could be processed in a practical setting either on the sensor or on a local mobile device while a person runs to allow for near real-time feedback to the runner on their performance.

One subject was assessed in this study to give a preliminary understanding of how foot acceleration data relates to kinematic changes due to fatigue. With only one subject it is not possible to be confident that such relationships exist in the wider athletic population. Testing on more athletes is necessary to determine if the relationships found in this study carry over to a wider group of athletes.

VI. Conclusion

The results described here suggest that using variables from a simple accelerometer on the shoe could potentially provide important information to runners regarding their running technique. Future research should investigate whether similar relationships between accelerometer variables and kinematic data exist in a wider group of athletes.

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