Out of the Lab and Into the Woods: Kinematic Analysis in Running Using Wearable Sensors

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ABSTRACT
Injuries in running are often provoked by fatigue or improper technique, which are both reflected in the runner's kinematics. State of the art research on kinematics in sports is using optical motion capture systems that are inaccessible to most athletes. This paper demonstrates the potential of wearable sensors for runners' kinematics analysis. We present a user study including 21 subjects of different running experience that performed an exhausting run on a conventional outside track wearing ETHOS units. For performance level assessment, training assistance, and fatigue monitoring we extracted the foot contact duration, the foot strike type, and the heel lift as kinematic parameters. A questionnaire revealed that subjects perceived the sensors as comfortable to wear and would use them on a regular basis. We concluded that wearable sensors provide a valuable tool for runners, from beginners to experts, for running technique assessment.

Author Keywords
Sports, wearable system, performance evaluation.

ACM Classification Keywords
I.5.4 Pattern Recognition: Applications—*Signal Processing*

General Terms
Algorithms, Experimentation, Measurement.

INTRODUCTION
Long distance running has become a popular sport for the masses, alone in the US about two Marathon competitions are carried out per day[1]. The motivation for runners to pursue this sport is not limited to improvement of the personal record performance, a query revealed that running is "like therapy, or an antidepressant". However, everybody can run but might not do it properly. About 65 % of runners are injured in an average year[2]. Poor running technique and fatigue increase the risk of injury [1]. Both are reflected in the runner's kinematics which is traditionally monitored and analyzed using optical motion capture systems [2, 9]. The high costs of such systems and marginal availability restrict assessments to professional runners in a constrained environment [2].

However, continuous advances in sensing technology emerged miniature sensors enabling body worn sensing and analysis of human motion [7]. Following this trend, we developed a small and lightweight inertial measurement unit (IMU), specifically optimized for long-term, out of the lab measurements.

In this work, we demonstrate the potential of ETHOS for kinematic parameter assessment in endurance running, which makes great demands especially on wearability and comfortable sensor attachment. We present a user study, in which each runner wore 12 ETHOS units throughout an exhausting run. We extracted kinematic features from the sensors to assess the three main application areas skill level assessment, fatigue monitoring, and training assistance. From our observations we found that kinematic features from two sensors, on the foot and on the shin, suffice to cover these. In this work, we present the kinematic feature extraction and evaluation based on these two sensors. Table 1 illustrates the kinematic features, congruent sensor position, and the covered application areas.

		application		
		skill level assessment	fatigue monitoring	training assistance
kinematic feature	Foot Contact (foot sensor)	x	x	
	Foot Strike Type (foot sensor)		x	x
	Heel Lift (shin sensor)	x	x	

Table 1. Overview of calculated kinematic features and corresponding application areas.

ETH ORIENTATION SENSOR (ETHOS)
ETHOS constitutes an inertial measurement unit (IMU), which is optimized for long-term, out of the lab recordings [3]. Each unit comprises a 3D accelerometer, a 3D gyroscope, and a 3D magnetic field sensor. The central processing unit of ETHOS is a 16-bit dsPIC. Sampled data can be stored to a local 2 GB microSD card, or be transmitted via USB. Wireless connectivity is provided by an integrated ultra low power ANT+ module that allows for interfacing of other ETHOS units or sampling of data provided by external ANT+ compatible devices such as heart rate belts or GPS re-

[1] http://www.runningintheusa.com/More/Default.aspx
[2] http://www.sportsinjurybulletin.com/

ceivers. Each ETHOS unit is equipped with a real time clock (RTC) for synchronization of multiple devices.
Its elongated design (WxLxH = $14\,\mathrm{mm} \times 45\,\mathrm{mm} \times 4\,\mathrm{mm}$) is optimized for attachment along human body limbs. We developed flat and bracelet housings (compare Fig. 1), that contain the sensor, a battery, and a switch. The overall system weighs $27\,\mathrm{g}$ for the round housing and $22\,\mathrm{g}$ for the flat housing, respectively.
In a typical ETHOS use case, in which data are sampled at a frequency of $128\,\mathrm{Hz}$ and stored locally, a system runtime of seven hours is achieved. The orientation is calculated from sensor data by fusing acceleration, gyroscope, and magnetic field data using a state of the art complementary filter [10]. While its low computational requirements permit an online implementation on the sensor, it shows sufficient accuracy for most applications. We achieved an average RMS error in 3D orientation of $1.17°$ for all axes during experimental characterization, wherein an optical motion capture system (Vicon) was utilized as a reference.

EXPERIMENT DESIGN

Respective data used for assessment of kinematic parameters was recorded during a $45\,\mathrm{min}$ run on an outside track. 21 healthy subjects (13 men, 8 women) with an average age of 33.8 ± 8.4 years participated in the experiment. Table 2 details information on the subjects including weekly training amount, which was ground truth for classification into skill level groups. Chosen participants showed a balanced skill level distribution ranging from beginners to competitive runners.

skill level group	training [km/week]	speed [km/h]	number of subjects
beginner	0–5	9–10.5	6
intermediate	5–25	10.5–12	6
advanced	25–45	12–14.5	6
expert	> 45	14.5–17.8	3

Table 2. Skill level groups, their amount of training per week, the speed range during the $45\,\mathrm{min}$ run, and the number of subjects participating in this study of the individual performance group.

Subjects were instructed to maintain a speed of 75–85 % of their maximum aerobic speed to provoke a change in running kinematics due to fatigue. Maximum aerobic speed was conducted preliminary to the study in a standardized endurance test on a treadmill. The run was performed on an outside track commonly used by runners, speed was monitored by GPS. The track showed a circular shape with a total length of $550\,\mathrm{m}$, which allowed for permanent supervision of the subjects by an assistant for safety reasons. Subjects were filmed with a video camera at a defined checkpoint and a turn-based feedback on the lap time was provided.
Figure 1 depicts the attachment and the positions of the two ETHOS units on the foot and the shin used for analysis in this work. ETHOS data were sampled at $100\,\mathrm{Hz}$ and stored to a local microSD card for subsequent offline analysis. Temporal alignment of simultaneously recorded data was guaranteed by a dedicated hub that synchronizes the onboard real time clocks (RTC) of attached ETHOS units.
The presented experiment design was authorized by an ethics commission. Subjects signed an informed consent before participation.

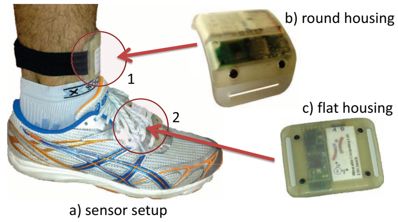

Figure 1. Runner equipped with ETHOS devices (encircled) on foot and shin (a). Close up of the two housing types (round (b) and flat (c)).

FOOT CONTACT DURATION

The normalized foot contact duration (NFC) denotes the percentage of time one foot is on the ground during one step cycle. NFC decreases with increasing skill level, since shorter contact allows for faster running [2].
Figure 2 depicts the magnitude of the right foot's acceleration (sensor 2, Fig. 1) for one step and subdividing step phases. As depicted in Fig. 2 the (absolute) foot contact duration of step k corresponded to the time interval in which the magnitude of the foot's acceleration remained stable below a defined threshold after a foot strike ($FS(k)$). During this time, the foot was on the ground and was not exposed to dynamic accelerations as it occurred when the foot became airborne. The subsequent toe off ($TO(k)$) was thus detected when the acceleration magnitude exceeded a defined threshold of $2\,\mathrm{g}$.
The normalized foot contact duration is calculated by dividing the foot contact duration ($TO(k) - FS(k)$) by the step cycle duration ($FS(k+1) - FS(k)$).

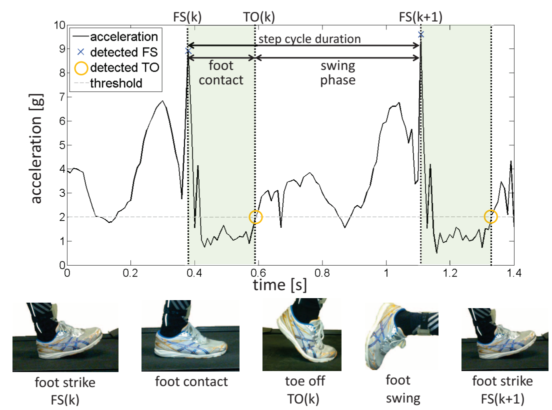

Figure 2. Acceleration magnitude of the foot mounted sensor (sensor 2, see Fig. 1). Detected foot strikes $FS(k)$ are indicated by 'x'. Each step cycle is subdivided into foot contact and swing phase. The toe off ($TO(k)$, indicated by 'o') separates both phases and is detected by a threshold (dashed horizontal line).

Figure 3 depicts NFC of a beginner and an expert runner during the whole run. We observed that the expert's foot contact is shorter, which is congruent with related work [2]. Additionally, the beginner's NFC showed greater variations throughout the run compared to the expert, and increases over time, probably due to fatigue. From GPS measurements we observed that the beginner runner was not able to maintain her individual speed. Since step duration was kept stable, we concluded that flying phase was shortened.
Moreover, our results indicated that an analysis of the normalized foot contact duration shows potential for skill level assessment and fatigue monitoring.

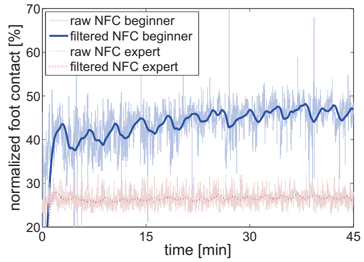

Figure 3. NFC of beginner and expert during the 45 min run. NFC constitutes the time the foot is on the ground during one step. It is lower for the better runner. For the beginner, an increase of NFC can be observed over the course of the run.

FOOT STRIKE TYPE

Depending on an individual history of injuries and training distance, most runners train to maintain a specific foot strike type. Automated assessment of the foot strikes provides valuable information to runners of all skill levels. While it presents a diagnostic tool for ambitious runners, it can be used for beginners as a basis for instructions on stretching after the workout to help prevent injuries.

Three different foot strike types are common, named after the part of the foot that touches the ground first: (1) heel, (2) midfoot, or (3) toe strike. Each of the strike types has advantages and disadvantages. Heel strikers have less stress on their calves and Achilles tendon but are slowed down. As the knee is not bent during the strike it experiences high impact stresses, which promotes injuries over time [4]. Midfoot runners experience more stress on the calves and Achilles tendon but absorb shock better since the knee is bent. Most long distance runners are midfoot runners. Toe striking contributes to a better form and faster running but it keeps calf muscles contracted contributing to various injuries [8]. However, toe strikers experience less stress on knees and ankles.

The analysis of the foot strikes was performed stepwise based on the gyroscope data recorded by the right foot mounted sensor (sensor 2, Fig. 1). Foot strikes were characterized by the forward-backward rolling characteristics of the foot, which correspond to a rotation about the lateral axis of the sensor. Figure 4 displays a calibrated gyroscope signal for a typical heel, midfoot, and toe striker. The ground truth of foot strike type was derived from video observations. A heel striker showed a high negative peak in rate of turn at foot strike, which indicated the rolling of the foot from heel to toe. The midfoot striker showed a lower rate of turn in both directions, and the toe striker showed a higher positive peak around foot strike evoked by rolling from toe to heel.

For discrimination of the strike type, we spotted the minimum and maximum peak of the unfiltered foot's pitch rate of turn in a 0.2 s window around foot strike (FS). Figure 5 depicts a scatter plot of these features for the whole duration of the experiment of a typical heel, midfoot, and toe runner. The plot indicates that the two features are sufficient for discrimination of the foot strike type. This cluster forming can be observed for any runner combinations of the individual foot strike types. Figure 6 details the chronological development of the strikes during the 45 min run by an expert runner. The plot indicates a slight tendency towards midfoot striking over time, since the mean of a 5 min sliding window moves from the upper right to the lower left (compare Fig. 5). This trend indicated muscle fatigue and could be utilized for retrospective assessment of the training quality. We conclude that foot strike type analysis enables training assistance and fatigue monitoring.

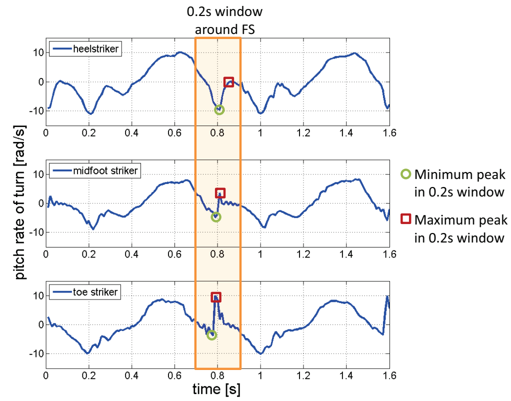

Figure 4. Foot's pitch rate of turn of a typical heel, midfoot, and toe striker (sensor 2, Fig. 1). For classification, minimum and maximum peak within a 0.2 s around foot strike were detected.

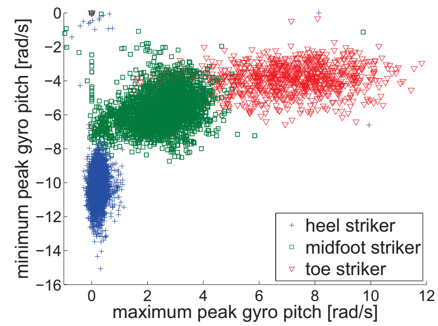

Figure 5. Clusters discriminate heel, midfoot, and toe striker. The two features are minimum and maximum peak of foot's pitch rate of turn within a 0.2 s window around foot strike.

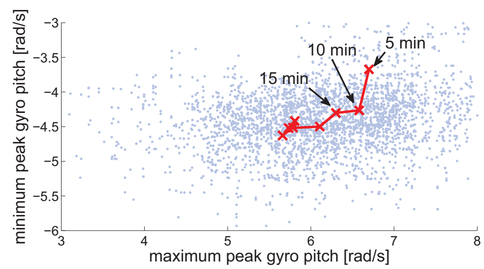

Figure 6. Traveling center of toe striker toward a more midfoot striking during the 45 min run. Mean travels from upper right to lower left.

HEEL LIFT

The Heel Lift (HL) denotes the amount of foot lifting, hence, flection of the knee during the swing phase. An increased heel lift decreases the effective leg length, leading to a decreased moment during forward swing. Research concluded that high heel lift allows for energy efficient and fast running [6]. Moreover it was shown that heel lift increases with speed, and tends to decrease during exhaustive runs owing to muscle fatigue.

We derived the HL metric from orientation data of the sensor attached to the right shin (sensor 1, Fig. 1). It was calculated as the maximum pitch angle of the shin during individual step cycles. An angle of $0°$ equals normal standing, i.e. the shin is vertical to the ground.

Figure 7 details the averaged heel lift for skill level groups for the first, the middle, and the last 5 min of the run. The bars indicate that participants of higher skill level groups performed heel lift to a greater extent (Fig. 7). Our observation was congruent to movement sciences' findings that heel lift increases with speed and indicates an efficient running technique [6]. Independent of the skill level, heel lift decreased through the course of the run due to progressive muscle fatigue. Since fatigue promotes the risk of injuries, an indicator providing feedback on exhaustion could help to assess running technique and prevent injuries.

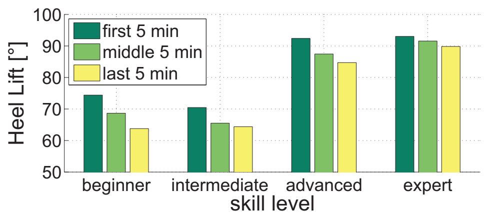

Figure 7. Heel lift of the right shin (sensor 1, Fig. 1) of the different skill level groups during the exhaustive outside run. Bars indicate the change of *HL* from the first 5 min to the middle and last 5 min of the run.

FEEDBACK ON SENSOR WEARABILITY

Subsequently to the experiments all subjects were asked to complete a questionnaire concerning wearability of sensors. Evaluation was based on the Comfort Rating Scales (CRS) introduced by Knight et al. [5]. Knight found that comfort should be assessed over multiple dimensions, including emotional, perceptive and physical components. In a self-administered assessment, subjects graded the following aspects from 0 (low) to 10 (high):

Emotion: I am worried about how I look when I'm wearing this device. I feel tense or on edge because of wearing the device.
Attachment: I can feel the device on my body. I can feel the device moving.
Harm: The device is causing me some harm. The device is painful to wear.
Perceived Change: Wearing the device makes me feel physically different. I feel strange wearing the device.
Movement: The device affects the way I move. The device inhibits or restricts my movements.
Anxiety: I do not feel secure wearing the device.

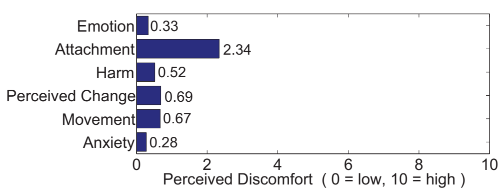

Figure 8. Mean CRS of sensor wearability for all subjects.

Figure 8 depicts results of the CRS. The attachment dimension scored the highest CRS with an average of 2.34, while the anxiety dimension obtained the lowest with 0.28.
In addition to the CRS subjects were asked if they would wear ETHOS on a regular basis as a personal trainer, and achieved an average rating of 8.2 (0 equals "no", 10 equals "yes").

We concluded from the CRS that ETHOS units were perceived as comfortable to wear, and did not constrain movements of the subjects during running. User acceptance could possibly be further improved by removal of spare sensors that were not considered in this study or integrating sensors in shoes or clothes.

CONCLUSION

In this work, we demonstrated the potential of wearable technology for assessment of kinematic parameters using the example of running. We introduced a miniature IMU that was designed for long-term monitoring of human movement outside the lab. We investigated wearability and assessment of established kinematic parameters in a user study with 12 runners of different skill levels. Each runner wore a set of 12 ETHOS units and performed an exhausting run on an outside track for a duration of 45 min. We found that from the 12 units a minimal set of two units attached to the foot and shin is sufficient to cover the desired application areas skill level assessment, fatigue monitoring, and training assistance. Inference of kinematic parameters using wearable devices enables a transition from subjective self-assessment to objective assessment. The automatically calculated parameters can be provided to doctors or athletes for post training analysis.
The significance of our approach was confirmed by a questionnaire, in which subjects stated that the experienced wearing comfort approves the acceptance of sensors. We concluded that wearable technology opens possibilities for technique improvement and injury risk reduction to a wide spectrum of athletes.

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