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Continuous three dimensional analysis of running mechanics during a marathon by means of inertial magnetic measurement units to objectify changes in running mechanics

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ABSTRACT

Recent developments in wearable and wireless sensor technology allow for a continuous three dimensional analysis of running mechanics in the sport specific setting. The present study is the first to demonstrate the possibility of analyzing three dimensional (3D) running mechanics continuously, by means of inertial magnetic measurement units, to objectify changes in mechanics over the course of a marathon.

Three well trained male distance runners ran a marathon while equipped with inertial magnetic measurement units on trunk, pelvis, upper legs, lower legs and feet to obtain a 3D view of running mechanics and to asses changes in running mechanics over the course of a marathon. Data were continuously recorded during the entire 42.2 km (26.2 Miles) of the Marathon. Data from the individual sensors were transmitted wirelessly to a receiver, mounted on the handlebar of an accompanying cyclist. Anatomical calibration was performed using both static and dynamic procedures and sensor orientations were thus converted to body segment orientations by means of transformation matrices obtained from the segment calibration. Joint angle (hip, knee and ankle) trajectories as well as center of mass (COM) trajectory and acceleration were derived from the sensor data after segment calibration.

Data were collected and repeated measures one way ANOVA's, with Tukey post-hoc test, were used to statistically analyze differences between the defined kinematic parameters (max hip angle, peak knee flexion at mid-stance and at mid-swing, ankle angle at initial contact and COM vertical displacement and acceleration), averaged over 100 strides, between the first and the last stages (8 and 40 km) of the marathon. Significant changes in running mechanics were witnessed between the first and the last stage of the marathon.

This study showed the possibility of performing a 3D kinematic analysis of the running technique, in the sport specific setting, by using inertial magnetic measurement units. For the three runners analyzed, significant changes were observed in running mechanics over the course of a marathon. The present measurement technique therefore allows for more in-depth study of running mechanics outside the laboratory setting.

1. Introduction

Running is a popular sport that is characterized by a high-incidence of injuries (van Gent et al., 2007). Etiology of running related injuries is believed to be multifactorial but still not fully understood (Hreljac, 2005; van der Worp et al., 2012). Fatigue is considered to be one of the underlying factors of injuries, as it can cause changes in running mechanics over the course of a prolonged run (Clansey et al., 2012). Analysis of these changes will provide insight into the effects of fatigue on running mechanics and, possibly, injury risk. The effect of fatigue has been studied extensively, however the exact influence on running mechanics and hence, injuries, still remains unclear (Mizrahi et al., 2000a, 2000b). This might be a consequence of the limitations of analyzing running mechanics in the laboratory setting.

1.1. Limitations of analyzing running mechanics in the laboratory

Most studies on the influence of fatigue on running mechanics have been performed within the limitation of a controlled laboratory

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setting on walk-ways and (instrumented) treadmills (Derrick et al., 2002; Hayes et al., 2004; Dierks et al., 2010; Voloshin et al., 1998; Mercer et al., 2003; Mizrahi et al., 2000a, 2000b; Koblbauer et al., 2014). Walkways are limited in length and therefore a-specific for outdoor running. Additionally, mechanics of overground and treadmill gait and running were supposed to be similar (van Ingen Schenau, 1980; Riley et al., 2007, 2008). However, more recent studies conclude that there are kinematic differences between the two settings (van Caekenberghe et al., 2013; Garcıa-Perez et al. 2013), making it questionable to extend results of lab-based studies to outdoor running. It is therefore important to study the effects of fatigue on running mechanics in the sport-specific setting. This is challenging since current three dimensional (3D) motion capture systems are mostly bound to the laboratory setting. In addition, it is more difficult to control the level of fatigue outside the laboratory due to the possible and unpredicted changing of environmental factors.

1.2. Analysis of running mechanics outside the laboratory

A marathon is a setting in which fatigue build up is obvious. Since it has been shown that a marathon causes significant levels of fatigue (Del Coso et al., 2013), a marathon is a perfect real-world setting to study the effects of fatigue on running mechanics. Recent studies have used video analysis to observe fatigued running during a marathon (Chan-Roper et al., 2012; Larson et al., 2011). These studies have increased external validity over lab-based studies and provided valuable insights on the effect of fatigue on running mechanics in the sport-specific setting. Both studies showed changes in running mechanics over the course of a marathon. However, generalization is limited since video analysis is confined to two dimensional analyses within a limited measurement volume. As a consequence, only a few strides can be analyzed. Morin et al. (2011) and Degache et al. (2015) took a different approach and used a 7 m long electronic walkway, equipped with a series of pressure sensors, to study running mechanics and spring-mass behaviors before, during and directly after two different ultra-marathon events of 160 and 330 km respectively. By using an electronic walkway, they were able to capture multiple strides and analyze spatiotemporal, kinetic as well as kinematic parameters. Running mechanics and spring mass behavior of the leg did change, mainly in the first half of the ultra-event, possibly as an adaptive strategy to anticipate overload. Although multiple strides could be measured, the measurement set up only allows for the analysis of running mechanics at selected parts of the race and was not able to analyze joint angles and not suitable for continuous analysis.

1.3. Use of inertial sensors in sports

Recent developments in wearable and wireless sensor technology allow for a continuous 3D movement analysis outside the laboratory. Inertial sensors, also called inertial measurement units (IMUs) or inertial magnetic measurement units (IMMUs, containing also a magnetometer) have been successfully used for 3D gait analysis (i.c. walking) and have shown good accuracy compared to optical motion analysis systems (Dejnabadi et al., 2006; Roetenberg et al., 2007). Inertial sensors have been used in sports science as well to continuously analyze movement. Recent (systematic) reviews by Dellaserra et al. (2014), Chambers et al. (2015) and de Magalhaes et al. (2015) showed extensive use of IMUs to quantify sport-specific movements. It can be concluded from these reviews that IMUs show acceptable levels of accuracy and reliability, that they have the ability to support performance assessment and that they have great potential to detect sport-specific movements and are capable of quantifying sporting demands that other technologies cannot detect. It can also be concluded that multiple sensor models, in contrast to single sensor set-ups, can be a tool to understand specific movements into greater detail and to provide feedback on correct and incorrect techniques.

1.4. Analysis of running mechanics with inertial sensors

For the purpose of quantifying movement patterns, in particular gait and running, inertial sensors have been used to define spatiotemporal and kinematic parameters (Aminian et al., 2002; Findlow et al., 2008; Mayagoitia et al., 2002; Favre et al., 2008; Picerno et al., 2008; O'Donovan et al., 2007). None of them actually analyzed 3D kinematics, however. Lee et al. (2010) and Bergamini et al. (2012) used a single inertial sensor, mounted to the sacrum and trunk respectively to obtain spatiotemporal parameters in running and were able to estimate stance, step and stride duration during sprint running.

Inertial sensors have not been used frequently, however, to study running mechanics. Strohrmann et al. (2011, 2012) were able to record continuous motion data during running inside and outside the lab using wireless IMMUs. During exhaustive 45 minute runs on the treadmill and on the track they identified variables that were influenced by fatigue. Parameters were identified that changed under fatigue for all runners, and that changed depending on the skill level of the runner and for individual runners. However, in these studies each IMMU, corresponding to each body segment, were not linked to a biomechanical model, rendering it impossible to relate different sensors to determine joint angles. A segment calibration, that registers the relation between segments and sensors, would have been necessary in order to create a biomechanical model, allowing actual 3D kinematic analysis of running based on data from IMMUs.

1.5. Aim of the study

Since, up till now, it has not been possible to study 3D kinematic changes in running mechanics outside the laboratory and during an actual competition, the aim of this study is to present a measurement set-up based on inertial magnetic measurement units, to perform a continuous 3D kinematic analysis of running technique during the course of an actual marathon to objectify changes in running mechanics.

2. Methods

2.1. Experiment design

Five well trained athletes volunteered to participate in our study. All participants were experienced runners with an expected marathon finish time around 3 h (this criterion was set as a result of the battery life of the sensors). They reported no history of injuries in the previous year. The experimental protocol was approved by the local Medical Ethical Committee and all participants signed informed consent prior to participation. Measurements were performed during the 2014 Enschede Marathon with full-cooperation of the organizing committee. Due to technical problems (signal loss), only data from three runners (38.7 ± 8.2 years, 182 ± 2.4 cm, 73 ± 3.7 kg) could be collected for the entire duration of the race and thus analyzed (Table 1).

Table 1
Characteristics of the three runners analyzed.

Runner	Sex	Age (years)	Height (cm)	Weight (kg)	Finish time (h:min:s)
R1	Male	35	185	72	2:59:49
R2	Male	31	182	78	3:14:44
R3	Male	50	179	69	3:01:58

Runners were equipped with 8 IMMUs on trunk (sternum, just below the sternal angle), pelvis (on the sacral bone between left and right iliac spine), upper legs (on tibial tract, halfway iliac crest and lateral condyle of the tibia), lower legs (at the lower third of the medial surface of the tibia) and feet. To make sure sensors were firmly attached yet not restricting movement, sensors were attached to the skin with double-sided adhesive skin tape and fixed with kinesiotape. The foot sensors were fixed with the use of foot clips laced on the shoes and secured with tape. After sensor attachment static and dynamic calibration procedures were performed to obtain segment calibration.

Data were continuously recorded during the entire 42.2 km (26.2 Miles) of the Marathon. To ensure manageable-sized files and prevent orientation drift, data was saved every 15–20 mins at predefined moments in the race, after which recording was continued.

2.2. Measurement device

Wireless IMMUs (MTw, Xsens Technologies B.V., Enschede, the Netherlands) were used. Each IMMU contains a 3D accelerometer (scale: $\pm 160\ \text{m/s}^2$, noise: $0.003\ \text{m/s}^2/\sqrt{\text{Hz}}$, internal sampling rate: 1800 Hz), a 3D gyroscope (± 1200 deg/s, $0.05\ \text{deg/s}/\sqrt{\text{Hz}}$, 1800 Hz) and a 3D magnetometer (± 1.5 Gauss, $0.15\ \text{mGauss}/\sqrt{\text{Hz}}$, 120 Hz). The sensors are 34.5 (W) $\times$ 57.8 (L) $\times$ 14.5 (H) mm in size, with a mass of 0.027 kg and powered by a battery. Data were transferred wirelessly to a base station (Awinda Master, mounted on the handlebar of the bicycle of an accompanying cyclist), with an update rate of 60 Hz and acquired on a tablet via USB. The antenna of the base station was raised high on the bike to ensure that other runners, road signs, etc. between cyclist and runner would not interfere with data transfer. Running velocity and distance covered were recorded simultaneously throughout the race using a GPS enabled watch (Garmin Forerunner 210, Garmin, Wichita USA).

2.3. Data analysis

Four stages of the Marathon were defined at which data acquisition of the participants was successful and the course was level and straight. These stages were at approximately 8, 18, 27 and 36 km of the Marathon. For each runner, data measured by the IMMUs positioned on the trunk, pelvis and right lower limb were analyzed.

For signal acquisition the Xsens software (MT Manager *4.2.1*, Xsens the Netherlands) was used and MATLAB *R2013a* (The MathWorks Inc., MA, USA) was used for data processing and analysis. The Xsens software uses a Kalman filter (Xsens Kalman Filter, XKF) to fuse the data of accelerometers, gyroscopes and magnetometers to estimate the orientation of each sensor. Sensor orientations were converted to segment orientations by means of transformation matrices obtained from segment calibration procedures. A transformation matrix, based on the static and dynamic calibration, was defined to determine the time-invariant relation between each sensor frame and the corresponding anatomical segment frame. For the static calibration, the gravitational vector was measured while the subject was standing still in upright position. The gravitational vector defines the longitudinal axis of the segment. For the dynamic calibration, the subject was asked to perform a set of flexion extension movements at the hip, knee and angle joints. The average angular velocity vector, measured by the IMMU's gyroscope, during these movements was assumed to correspond to the frontal/lateral segment axis. The sagittal segment axis is constructed using the vector cross product of the lateral and vertical axis. Finally, a strictly orthogonal right-handed frame is obtained by replacing the lateral axis by the cross product of the sagittal and vertical axis. Joint angle trajectories of hip, knee and ankle where then determined following the Cardan convention with an YZX sequence.

Step detection was based on raw inertial data acquired from the foot sensors. A peak detection algorithm is used to identify local maxima in the accelerometer magnitude $\left(\mathbf{a} = \sqrt{a_x^2 + a_y^2 + a_z^2}\right)$ evoked during foot strike (Strohrmann et al., 2012). The subsequent peak magnitude in the gyroscope signal, as a result of fast plantar flexion during push off, was marked as toe off (Bergamini et al., 2012; Sabatini et al., 2005). The number of samples per step, obtained during the step detection procedure, was divided by the update rate (60 Hz) to calculate step frequency. Subsequently, step frequency and average running velocity, based on GPS data, were used to compute step length.

Maximal values for hip and knee angle during mid-stance and mid-swing, and of the ankle angle at initial contact (IC), were determined based on the joint angle trajectories. Per stage, data were averaged over 100 strides. Normalized stance phase duration (expressed as a percentage of the total step duration) was defined as contact duration ($t_{\text{toe-off}} - t_{\text{initial-contact}}$) divided by step duration. The segment calibration procedure was applied on the raw accelerometer data of the sensor positioned at the pelvis and defined as center of mass (COM) acceleration. COM acceleration was then integrated twice and high-pass filtered to estimate COM trajectory (vertical displacement), according to the method developed by Floor-Westerdijk et al. (2012).

Repeated measures one way ANOVAs, with Tukey post-hoc test, were used to statistically analyze mean differences of the defined spatiotemporal and kinematic parameters between the different defined stages of the marathon for each runner. Confidence interval was set to 95%. For clarity purposes only differences between the first and last stage (stage 1 and 4 of the marathon) will be presented.

3. Results

Table 2 presents the velocity, stride length and step frequency (average $\pm$SD) for the three runners at the four defined stages during the marathon. Running velocity decreased significantly for one runner (R2, $p < 0.001$) while stride length decreased in two runners (R1 and R2) and increased in one runner (R3) between the first and last stage of the marathon ($p < 0.001$). Step frequency decreased in one runner (R1) and increased in two runners (R2 and R3) between the first and last stage ($p < 0.001$).

Table 3 shows the results about the kinematic parameters max hip angle, peak knee flexion at mid-stance and at mid-swing, ankle angle at IC, COM vertical displacement and acceleration (average $\pm$ SD, and standard error of the estimate (SEM)) for the three runners at the four stages. Changes in running kinematic were observed for all runners between stage 1 and 4 of the marathon. Max hip angle decreased in R1 ($p < 0.001$) and R2 ($p < 0.001$) and increased in R3 ($p < 0.001$) between stage 1 and 4. Peak knee flexion at mid-stance and mid-swing and ankle angle at IC decreased for all runners ($p < 0.001$) between stage 1 and 4. COM vertical displacement decreased significantly in R3 ($p < 0.001$) while COM vertical acceleration at IC increased in all runners ($p < 0.001$) between stage 1 and 4.

Typical examples of the kinematic parameters at the first and last stage (hip angle trajectory, knee angle trajectory, ankle angle trajectory, COM vertical displacement and acceleration) are displaced in Figs. 1 and 2.

4. Discussion and conclusion

The aim of this study was to present a measurement set-up based on inertial magnetic measurement units, to perform a continuous 3D kinematic analysis of running mechanics during an actual marathon. This study showed the possibility of performing continuous 3D kinematic analysis of the running technique during the sport specific setting and identified and objectified changes in both spatiotemporal and kinematic parameters over the course of the marathon in three runners. The presented measurement set-up can therefore present valuable information about running mechanics to runners, coaches and clinicians that has not been possible before. This information can possibly be used to aid injury prevention and assist performance enhancement.

Investigating changes in running kinematics, for instance as a consequence of fatigue, has long been limited to the more or less a-specific laboratory setting. In order to get insight into the specific challenges runners face outside the laboratory in real world, measurements need to be performed outside the laboratory in a setting as specific as possible. To our knowledge, this is the first study that actually analyzed 3D kinematics continuously outside the laboratory, by using inertial sensors, in the sport specific setting of running.

4.1. Spatiotemporal changes

The present study builds upon the existing body of knowledge on changes in running mechanics over a prolonged race such as a marathon in the sport specific setting. Spatiotemporal parameters like running velocity, stride length and step frequency changed in an individual way. This inter-individual variation is in line with Hunter and Smith (2007) who showed subject specific changes in

Table 2
Spatiotemporal results (velocity, stride length and stride frequency) for the three runners (average, SD and SEM) for the four stages. An asterisk denotes a statistical significant difference ($p < 0.05$) between stage 1 and 4.

Parameter	Stage	R1			R2			R3		
		Average	SD		Average	SD		Average	SD	
Velocity (km/h)	1	13.9	1.6		13.4	0.8		13.3	0.9	
	2	14.7	2.2		13.4	0.5		13.9	1.3	
	3	13.8	0.5		13.0	0.6		13.3	2.2	
	4	13.4	1.8	NS	11.9	0.6	*	14.0	1.3	NS
Stride length (m)	1	2.69	0.07		2.60	0.03		2.39	0.04	
	2	2.84	0.05		2.58	0.03		2.48	0.03	
	3	2.68	0.06		2.50	0.03		2.41	0.34	
	4	2.63	0.04	*	2.28	0.03	*	2.48	0.25	*
Step frequency (steps/min)	1	172.11	4.33		171.82	2.03		185.76	3.19	
	2	172.11	4.33		173.35	2.17		187.10	2.53	
	3	171.55	3.53		173.65	2.19		185.48	13.67	
	4	169.68	2.80	*	174.15	2.27	*	189.21	9.83	*

Table 3
Kinematic data (average, SD and SEM) for R1, R2, and R3 over the four stages. An asterisk denotes a statistical significant difference ($p < 0.05$) between stage 1 and 4.

Parameter	Stage	R1				R2				R3			
		Average	SD	SEM		Average	SD	SEM		Average	SD	SEM	
Max hip angle (deg)	1	51.51	1.86	0.19		41.77	1.15	0.11		43.85	1.38	0.14	
	2	51.78	1.58	0.16		42.22	0.62	0.06		42.76	0.84	0.08	
	3	51.66	1.64	0.16		42.56	0.66	0.07		47.35	1.94	0.19	
	4	49.74	1.22	0.12	*	38.60	0.89	0.09	*	45.73	1.11	0.11	*
Peak knee flex. midstance (deg)	1	45.15	2.19	0.22		31.11	1.34	0.13		47.15	1.15	0.12	
	2	36.27	1.09	0.11		31.05	0.77	0.08		44.51	1.20	0.12	
	3	31.91	1.24	0.12		31.75	0.69	0.07		42.30	6.09	0.61	
	4	39.99	1.33	0.13	*	30.63	0.86	0.09	*	44.89	3.86	0.39	*
Peak knee flex. midswing (deg)	1	96.69	2.25	0.22		98.54	1.06	0.11		86.49	2.51	0.25	
	2	94.01	1.19	0.12		100.16	0.89	0.09		83.34	1.58	0.16	
	3	100.33	1.73	0.17		97.48	1.00	0.10		83.78	3.82	0.38	
	4	90.36	1.74	0.17	*	94.25	1.31	0.13	*	82.13	2.87	0.29	*
Ankle angle at initial contact (deg)	1	5.64	2.52	0.25		3.93	2.20	0.22		10.80	3.58	0.36	
	2	−1.06	3.15	0.32		1.71	2.00	0.20		5.88	3.16	0.32	
	3	−4.85	3.09	0.31		8.44	2.48	0.25		1.67	3.20	0.32	
	4	−2.13	3.35	0.33	*	0.55	2.28	0.23	*	3.88	3.70	0.37	*
COM vertical displacement (m)	1	0.09	0.01	0.00		0.12	0.00	0.00		0.09	0.01	0.00	
	2	0.09	0.00	0.00		0.11	0.00	0.00		0.08	0.00	0.00	
	3	0.09	0.01	0.00		0.11	0.00	0.00		0.08	0.01	0.00	
	4	0.09	0.00	0.00	NS	0.11	0.00	0.00	NS	0.07	0.00	0.00	*
COM acceleration m/s^2	1	25.14	2.41	0.24		39.71	3.13	0.31		42.11	5.75	0.57	
	2	25.47	2.43	0.24		40.11	2.89	0.29		47.89	6.91	0.69	
	3	31.12	3.50	0.35		40.89	2.96	0.30		48.25	6.89	0.69	
	4	30.47	3.02	0.30	*	44.14	3.58	0.36	*	47.22	4.95	0.49	*

stride length and frequency during a fatiguing 1 h run. In our study, two runners ran slower towards the end of the marathon while one runners ran faster. Stride length decreased in two runners and increased in one runners while step frequency decreased in one runner and increased in two runners. The increase in step frequency is in line with the studies of Morin et al. (2011) and Degache et al. (2015) where an increase in step frequency was observed in runners during an ultra-marathon. The increase in step frequency might be an adaptive strategy to decrease or minimize the impact on the body. The decrease in stride length is probably caused by the reduction in running velocity since the decrease in stride length was accompanied by a reduction in running velocity while the increase in stride length was accompanied by an increase in running velocity. Chan-Roper et al. (2012) showed a decrease in stride length during a marathon for all runners. These runners all ran slower towards the end of the marathon.

4.2. Changes in kinematic parameters

The present study found kinematic changes over the course of a marathon for the three runners analyzed. When comparing the results of the present study with the literature, in line with Larson et al. (2011) and Clansey et al. (2012), changes were found in the ankle angle at IC. Furthermore, decreased peak knee flexion during stance is in line with the lab-based study of Mizrahi et al. (2000a, 2000b) but contradicts Derrick et al. (2002) who found increased peak knee flexion.

It can be questioned if the observed kinematic changes are a consequence of fatigue or part of an adaptive strategy to avoid future damage (Degache et al., 2015). The observed decreased peak knee angle at mid-swing, for instance, is in line with the study of Chan-Roper et al. (2012). This decrease does not necessarily need to be a consequence of fatigue and might be caused by the reduction

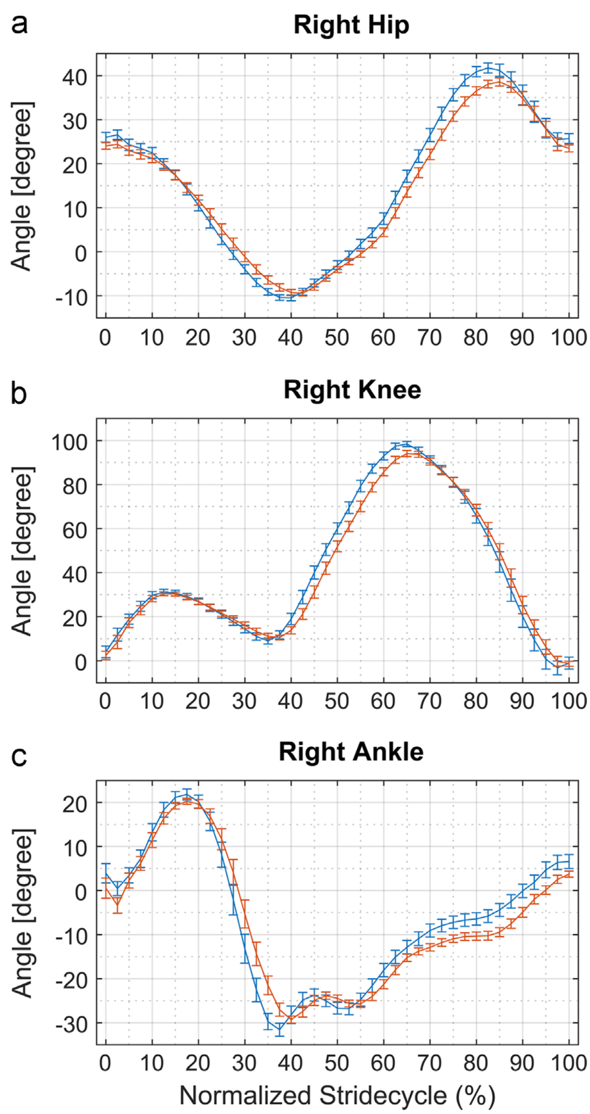

Fig. 1. Typical example of joint angle trajectories of R2 for normalized stride cycle, 1a represents the right hip angle, 1b represents the right knee angle, and 1c represents the right ankle angle. Presented are stage 1 and stage 4 with error bars.

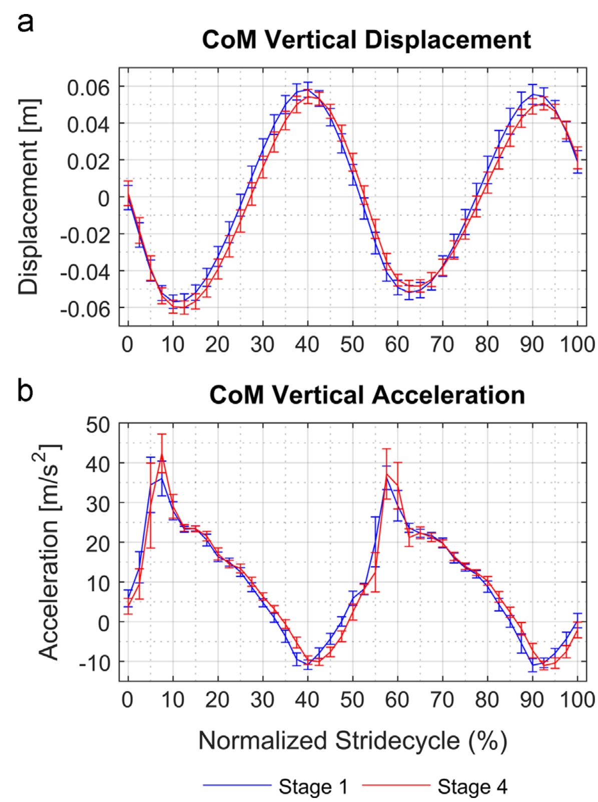

Fig. 2. COM vertical displacement and acceleration of R2 for normalized stride cycle, 2a represents COM vertical displacement, 2b represents COM acceleration. Presented are stage 1 and stage 4 with error bars.

in running velocity during the marathon (as observed in two of the three runners). Coventry et al. (2006) showed that kinematic alterations are used as an adaptation strategy to maintain shock absorption. Peak COM acceleration (derived from the sacral sensor) increased in all three runners. An increase in peak acceleration might indicate higher loading rates, a reduction in shock absorption quality and a higher impact on the body. Although the exact relation between impact and injuries is not clear yet, it has been shown retrospectively that increased dynamic loading rates are associated with injuries like tibial stress fractures (Milner et al., 2006; Clansey et al., 2012). The increased peak acceleration is in line with lab-based studies of Voloshin et al. (1998), Mizrahi et al. (2000a, 2000b), Derrick et al. (2002) and Clansey et al. (2012) who found increases in peak acceleration (at the tibia, sacrum or head) as a consequence of fatigue. Based on the higher peak acceleration seen in this study it can be assumed that the kinematic changes are an actual consequence of fatigue instead of a consequence of reduced running velocity.

4.3. Limitations

Measuring motion by means of IMMUs is promising but also challenging. From the five runners that were equipped with inertial sensors, data from only three of them were acquired successfully and suitable for analysis. For the other two, data were not usable since parts of the data were missing due to problems with transmitting the data from the sensor to the receiving device. If one or more sensors lose connection (due to distance, interference on the transmitting (2.4 GHz) frequency or battery life), spatio-temporal parameters and joint angles cannot be calculated. Interconnecting the sensors with wires and transmitting data from a central hub to the receiver could decrease the risk of data loss. However, this would have made the measurement set-up more invasive and less suitable for the setting presented in this study. Battery-life of the sensors may also be a problem for prolonged measurement. The sensors used in this study (Xsens MTw) had a battery-life of approximately three hours. This limited the inclusion of participants but created a rather homogeneous subject population. Recent developments in sensor technology have led to sensor battery-lives up to 7 h. This makes it easier to analyze a broader runner population and also to measure during fatiguing ultra-endurance events.

Due to the challenging aspects of measuring running mechanics outside the laboratory with IMMUs, the present study was only able to collect data on three runners. As a consequence, analysis on group level was not possible and observed effects of fatigue on running mechanics are confined to these runners only and may not be representative for other runners.

5. Conclusion

This study showed the possibility of performing a 3D kinematic analysis of running technique, in the sport specific setting, by using inertial-magnetic sensors. For the three runners analyzed, changes were observed in running mechanics over the course of a marathon. The presented measurement technique allows for more in-depth study of the running mechanics outside the laboratory and of the effects of fatigue on running mechanics in the sport specific setting. Future studies need to include more runners in order to investigate the assumed inter-individual different responses to fatigue and link these in a retrospective or prospective design to investigate on running injury mechanisms.

Conflict of interest statement

Authors declare no conflict of interest considering this study. The authors received no funding for performing the measurements and writing the manuscript.

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