UNIVERSITY OF TWENTE.

Faculty of Electrical Engineering, Mathematics & Computer Science

Intra-Subject Differences in IMU Measured Lower Limb Kinematics as a Result of Different Activity Intensity and Induced Fatigue

Matheas S. Moujaly

B.Sc. Thesis January 2021

Supervisors:
Luca Marotta, MSc
dr. Jasper Reenalda
dr. E.H.F. Van Asseldonk

Biomedical Signals and Systems
Faculty of Electrical Engineering,
Mathematics and Computer Science
University of Twente
P.O. Box 217
7500 AE Enschede
The Netherlands

Abstract

Fatigue detection in runners is a process that typically involves an expensive laboratory setup which results can not often be generalized to outdoor running activities performed by most people.

The study presented below has the objective of detecting the effect that running fatigue has on the biomechanics of different lower limb parts by using IMUs. With the hope of detecting behaviors that can be used to assess and indicate the onset of fatigue in runners.

Two different datasets of IMU data from runners performing tasks that differ in intensity and duration were analysed. The data was segmented into strides and parameters were looked at during different stages of each run and for each runner: the peak knee flexion (PKF) during swing and stance per stride, the peak hip flexion (PHF) during swing per stride, the peak hip extension (PHE) per stride, the ankle flexion at initial contact (AFIC) per stride, as well as the stride length (SL) and frequency (SF).

Intra and inter-subject differences were analysed and a statistical analysis revealed the following results: an increase in PKF stance with fatigue for all inexperienced runners, an increase in PHF swing for all experienced runners and an increase in PHE for all runners.

1 Introduction

Running is a popular sport among people from all ages and abilities. It is nonetheless a sport that presents risks of injuries caused by kinematic alterations in the cyclic movement of running. These alterations might be caused by the physical fatigue that comes with performing such an activity. [1]

Physical fatigue is qualified as the limitation of cognitive or physical functions as the result of perceived fatigability and physical or mental activities. [2] This definition helps perceiving fatigue from an empirical point of view, but lacks an objective quantification and description of fatigue.

Wearable physiological sensors have been used to fill that role, but current techniques are flawed. The measurement of physiological parameters, such as heart and breathing rate, relies on obstructive sensors that will influence the results in unwanted ways. Also, the use of in-lab instrumented treadmills and 3D motion capture systems has been proved to give measurements and results that can not be extended to outdoor running. [3]

An alternative would be to use IMUs (Inertial Measurement Units) that are cheap and unobstructive sensors that can be used to measure the acceleration of different body parts and limbs in the XYZ linear and rotational directions. These sensors can be used to qualify fatigue by analyzing the changes in the movement of limbs and body parts of different subjects that are put through activities of different intensity, duration and thus fatigue inducement.

This alternative, among others, has been tested and studied by researchers. They have explored the relation between fatigue inducement of different running activities and its effect on kinematic parameters of subjects from all age groups, genders and abilities. These researches have laid proofs for strong arguments that link fatigue to some kinematic alterations. Nevertheless, as Winter et al. discussed, mixed conclusions can be drawn from these studies with a numbers of factors influencing the kinematic alterations that show differences from study to study. [4]

This project's main objective is thus, to explore the relation between activity intensity and resulting fatigue by means of IMU measured lower leg kinematic parameters.

This will be done by analysing two available datasets of subjects performing running "tasks", that differ in intensity and duration, with IMUs attached to their limbs. The collected datasets of IMUs' accelerometer, magnetometer and gyroscope data will be compared internally (within subjects performing the same running "task") to analyse the changes in joint angles over the performance of the task as a result of the induced fatigue.

Nevertheless, another important part of this project will be the inter-subject (group level) comparison of datasets that will augment the intra-subject analysis by providing more insight into the influence of the different activities' intensity.

This would help quantify and understand how some gait parameters are influenced by the induced fatigue from a run, thus allowing us to qualify the fatigue inducement of a certain running activity based on measurable kinematic parameters.

2 Hypothesis and Research Question

It is hypothesized that every runner will have different gait and kinematic parameters that depend on their running style, experience and the conditions, among others, during the performance of the run. These parameters will also vary differently from one runner to the other. It would be therefore wiser to assess the differences in parameters for the same subject during different stages of the tiring activity he/she is performing in order to understand the effect fatigue has on these.

Thus, the research question that will be addressed in the scope of this project is:

Do intra-subject differences in IMU measured lower leg kinematics indicate an induced fatigue as a result of intense activities?

To answer such a research question, kinematic changes that are the most indicative of the influence of fatigue on a runner will be analysed first. The choice of these kinematic parameters will be guided by the analysis and conclusions of the extensive literature that has been dedicated to answering similar research questions. Nonetheless, these changes, or their lack of, will be tested for the influence of external variables such as the gender and experience of the runners in the datasets.

The results that are derived from this analysis can then be compared internally, between different runners of one set so that the effects of the runner's personal trait can be assessed. Afterwards they can be compared externally, between the two different sets of runners so that the effects of the intensity of the runs can be assessed.

3 Theoretical Background

3.1 Measurement Unit

The measurement device that was used to collect kinematic parameters on the runners' bodies is the MVN Link (XSens Technologies B.V., Enschede, The Netherlands). The MVN link is a set of body-wired sensors consisting of 8 MTx IMUs that weigh 10g per unit and have dimensions $36 \times 24.5 \times$ 10mm. The accelerometer range is 16g and the gyroscope's is $\pm$2000deg/s. Data collection is done at the rate of 240Hz. [5]

They were placed on 8 body locations, that represent different segments, during the experiment: sternum (the breastbone on top of the rib cage), pelvis (the large bone frame at the hips to which the lower limbs are attached), both thighs (leg part between the knee and hip), both tibias (the largest of the two bones between the ankle and knee) and both feet (lower extremity of the leg connected via the ankle). (See **fig.1**)

Figure 1: MVN Link with MTx sensors at (1) foot, (2)tibia , (3)thigh, (4)pelvis and (5)sternum.

The data from the different MTxs is transmitted using a specifically designed protocol to a master USB connected to the PC hosting Xsens software Xsens Device API. This software holds a Kalman Filter (XKF3-hm) that fuses the reading from the accelerometer, gyroscope and magnetometer in order to provide a highly reliable 3D estimate of the orientation of the different MTxs with respect to the Earth-referenced local frame. [6]

The MVN Analyze software is used to extract the calibrated sensor data from the IMUs for each segment; Such as the acceleration in all 3 directions, the angular velocity in all 3 directions, the 3D magnetic field and the free 3D acceleration[1]. [7]

In the end, the data that will be imported to MATLAB R2019a (MathWorks Inc., MA, USA) for further analysis is composed of: [6]

- The orientation, positioning, acceleration and velocity of segments, such as the sternum, in all 3 directions in a right-handed Cartesian coordinate system for which X is positive when moving forward along the horizontal plane, Y is lateral to body and Z is along the vertical to the body.
- The angular velocity and acceleration of these segments for rotation around the axis defined in the previous point.
- The joints angles, such as the knee, in all 3 directions with Z coordinates representing extension/flexion in the sagittal plane, X representing abduction/adduction in the frontal plane and Y coordinates representing internal/external rotation in the transverse plane.

[1]Acceleration to which the gravity component has been substracted

3.2 Gait Parameters

H.G.Chambers et al. defined the human gait cycle as "the movement from one foot strike to the successive foot strike on the same side".

A regular gait cycle is divided in two main phases; The stance phase, that starts with the initial foot strike and ends with the toe-off moment from the same leg, and the swing phase, that starts with toe-off and ends with the initial foot strike. (See **fig.2**) [8]

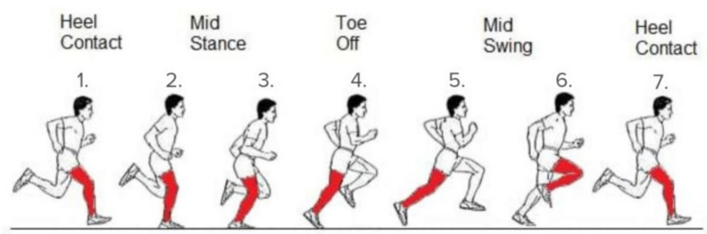


Figure 2: Running gait cycle. *Adapted from The Motion Mechanic.* [9]

From the data imports to Matlab discussed in **section 3.1**, spatio-temporal parameters were extracted such as the successive foot strike and toe-off moments on one foot that were detected via the peak downward velocity of the pelvis. These help in the segmentation of the run into different strides (gait cycles) that will be analyzed further in order to describe the gait of the different runners and extract relevant parameters from it.

3.2.1 Relevant Parameters and their extraction

S.Winter et al. conducted a review of different researches that analyse the kinematic changes caused by fatigue. They only took a look at researches that involve runners running to exhaustion or more than 3000m. [4]

This review can be taken as a guide when choosing which kinematic and gait parameters to analyse in this research. Findings that Winter et al. suggest are from "high quality" researches and/or show significant variation in the parameters with fatigue are discussed in this section.

It should also be noted that only parameters that can be measured within the scope of this study are taken as well. Arm movement for example can not be analysed with the set of sensor locations discussed in **section 3.1**.

In the context of this study, only the variation of joint angles in the sagittal plane of the dominant leg will be analysed. Winter at al., Chan-Roper et al. and other papers studied these parameters and made conclusions about their variation with fatigue that are presented in the following paragraphs. [4] [10]

Peak Knee Flexion , or PKF, represents the maximum angle between the tibia and the vertical in the sagittal plane. It is interesting to look at knee flexion during swing and stance phases.

It can be derived from the pitch angle of the knee joint, and these readings can be averaged per stride cycle to derive the PKF per stride for different stages of the run.

In the context of this study, the PKF will be extracted by taking the flexion/extension angle of the knee joint that is provided as discussed in **section 3.1**.

M. Chan-Roper et al. proved that there is a significant increase in PKF during swing phase (4.3% on average) and a significant decrease during stance phase (3.2% on average) that come with fatigue during a marathon run with experienced runners. [10]

Reenalda et al. confirm these findings, although with a less exhaustive protocol: less participants, 10 to Chan-Roper's 179, and only a 20 minutes run to Chan-Roper's marathon. [11]

Koblbauer et al. reported that for novice runners in mid-distance runs, the PKF swing indeed increases, but as opposed to the previous findings, the PKF stance increases significantly. [1]

Peak Hip Flexion , or PHF, can be derived from the pitch angle of the hip IMU, this reading can be averaged per stride cycle to derive the PHF per stride which occurs during swing.

In the context of this study, the PHF will be extracted by taking the flexion angle of the hip joint that is provided as discussed in **section 3.1**.

Chan-Roper et al. proved that the PHF increases in mean value with fatigue for experienced runners in long distance runs (7.4% on average). [10] Koblbauer et al. corroborate these results with a reported increase of PHF during swing on average for novice mid-distance runners. [1]

Peak Hip Extension , or PHE, is defined the same as the PHF and can be derived and extracted with the same method. The PHE is observed just before the toe-off moment of the stride.

Chan-Roper at al. reported a significant decrease in PHE at TO with the evolution of fatigue in long distance marathon runners (29.7% on average). Meanwhile Koblbauer et al. reported an increase in PHE at fatigue for mid-distance novice runners. [10] [1]

Other Parameters that show more or less significant variance with fatigue, and that are of interest for this study, are: The step (or stride) frequency that has been proved to decrease with fatigue as the step (or stride) length increase; And the ankle flexion angle at IC, or AFIC, that increases with fatigue as runners tend to shift towards a more heel-strike like foot strike pattern. [4] [10] [12]

4 Methods

4.1 Datasets and Experimental Design

The subjects were selected from the University of Twente and its surrounding area, they had to have at least ran 15+km per week for the last six months and reported no history of injuries during the previous year. The experimental protocols were approved by the local medical ethical committee and all participants signed an informed consent form prior to participation.

The subjects had an average age of 27.7 ± 8.6 years, height of 179 ± 9.3 cm and weight of 70.1 ± 8.3 kg.

Subjects information 5+km run					
Males					
Subject	XP (Years)	Dominant	Foot strike	V(m/s)	Borg (Stages)
1	8	Right	Heel	3.76	6,8,14,13
2	9	Right	Middle	4.71	8,12,14,14
3	5	Right	Middle	5.05	6,13,14,14
4	0.5	Right	Middle	3.33	6,14.5,17,18
5	6	Right	Heel	3.33	6,14,17,18
Females					
Subject	XP (Years)	Dominant	Foot strike	V(m/s)	Borg (Stages)
6	3	Right	Heel	3.02	6,12,11,11
7	16	Right	Middle	3.33	6,12,12,11
8	7.5	Right	Heel	2.81	6,10.5,11,10
9	2	Right	Heel	2.71	6,10.5,11,11
10	1.5	Left	Heel	2.84	6,12,19,19

Table 1: Experience, dominant leg, foot strike type, velocity and Borg scale (per stage as discussed in **section 4.2**) of the subjects in the 5+km run.

Subjects information 8x400m run					
Subject	XP (Years)	Dominant	Foot strike	V(m/s)	Borg (L1,L8)
11	12	Right	Fore	5.14	7,11
12	7	Right	Middle	5.14	10,12
13	5	Right	Middle	5.33	11,14
14	10	Right	Fore	5.06	10,13
15	14	Right	Middle	5.33	11,15
16	4	Left	Middle	5	8,14
17	9	Right	Fore	5	11,12

Table 2: Experience, dominant leg, foot strike type, velocity and Borg scale (per stage as discussed in **section 4.2**) of the subjects in the 8x400m run.

The two datasets were recorded with the following protocols:

- **8x400m Run:** After a self selected warm up stage of 5 to 10 minutes, 7 highly experienced male subjects performed 8 consecutive 400m runs with short breaks in between on a 400m athletic track. These runs were performed at a constant velocity which is the average of each runners' personal best 5km run.

- **5+km Run:** After a self selected warm up stage of 5 to 10 minutes, 5 male and 5 female subjects performed a 4km run on the same athletic track. Halfway through this run, the subjects switched the running direction. This run was performed at a constant velocity which is the average of each runners' best 10km performance during the previous year.

These runners were then subject to a fatiguing protocol until their rate of perceived exertion (RPE) measured by means of a Borg Scale reached 16 on a scale from 6 to 20 which is considered to be a heavy level of perceived fatigue. [13] (See **fig.3**)

The protocol consisted of 4 to 12 phases of a 100m run that started at the constant velocity of the previous run with a 0.2km/h increment after each phase.

Afterwards they performed a 1.2km run around the track in the fatigued state at the previously selected constant velocity.

Borg's Rating of Perceived Exertion (RPE) Scale	
Perceived Exertion Rating	**Description of Exertion**
6	No exertion; sitting and resting
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard
16	
17	Very hard
18	
19	Extremely hard
20	Maximal exertion

Figure 3: Borg scale representation of the rate of perceived exertion. *Adapted from New Mexico State University.* [14]

Prior to the protocols, information about the subjects was collected and are presented in **table.1** and **table.2** above alongside the determined foot strike and velocity for each subject. The evolution of the RPE of the runners during the performance of the protocols was also recorded and the values for each stage are also represented in the tables. Foot strike pattern was determined with the help of an HD camera.

4.2 Data Analysis

In order to assess the variations in the different parameters, their mean is calculated at different stages of the run: the mean peak knee flexion per stride can be averaged per 400 meters stages of the 5+km run for example. A distance of 400m has been chosen per stage since it represents one lap on the athletic track and makes comparing different stages of the 5+km run with the laps of the 8x400m run more concise.

For the 5+km run, 4 different stages of 400m each are chosen since they could give a good insight into the evolution of the different parameters with the run (See **fig.4**).

Stage 1 represents the second 400m of the run, it has been chosen since it is speculated that the results of the first 400m could be influenced by the adjustment of the runner to the experiment and the measurement device at its beginning. Thus more insight could be gained into the evolution of the non-fatigued 4km phase of the run by comparing stages 1 and 2, which represents the last 400m of the run.

Stages 3 and 4 represent respectively the second and last 400m of the 1.2km fatigued run, the first 400m has not been chosen for the same reasons as the first stage, there is an adjustment to the fatigued run that might influence the results. Although some variations are observed between stages 2 and 3, end of "rested" run and middle of fatigued run, these can not be taken as following the same evolution as between the first 2 stages since there is the adjustment to the fatigued run that has to be considered and could influence these results.

The observed variations could be related to fatigue, but the adjustment to the fatigued run protocol has to be considered when analysing the parameters differences between these two stages.

Thus, in the case of the 5+km run, stages 1 can be considered to be a rested phase, stage 2 can be considered a mildly fatigued stage as opposed to the heavy fatigue expected in stages 3 and 4 and that can be seen in the Borg scale evolution of **table.1** and **table.2** for most subjects.

For the 8x400m run, two stages are chosen for analysis, the first lap and the last lap. Since there could be minimal variations between each lap for the experienced runners of this dataset, it is considered better to look at the overall total variation that occurs between the beginning and end of these runs.

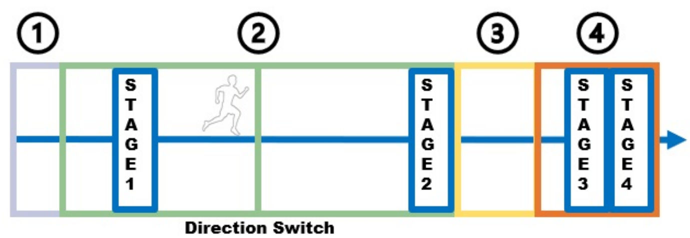


Figure 4: Representation of the different phases and selected stages of the 5+km run: (1)Warm-Up, (2)4km "rested" run, (3)Fatiguing protocol, (4)1.2km fatigued run.

4.2.1 Statistical Analysis

In order to observe if there is any significant change with regards to the mean at different stages of the run, a repeated measure one-way ANOVA test will be performed with the help of the IBM SPSS statistics 25 software. The confidence interval will be set at 95%, meaning that the significance value p should be under 0.05 for the mean to be considered to have varied significantly and thus to consider the change in parameter to be pronounced enough and relevant. [15]

This ANOVA test is used as an indicator that differences are indeed found between the means at different stages, but in order to assess which stages vary significantly from the others in detail, a Tukey Post Hoc test will have to be performed again with SPSS. This test is a continuation of the ANOVA test and will draw up a more detailed comparison of the means with regard to each stage. [15]

It should be noted, that some assumptions are not met for the utilization of the one-way ANOVA on these datasets (such as the independence of measurements), nevertheless the tests will still be used as other tests that were ran such as a Regression analysis or a T-test allow to take away the same conclusions as the ANOVA Test which is more insightful when utilized with a Tukey Post-Hoc test as many moments of the 5+km run are compared. [15]

5 Results

In this section, the changes in lower leg kinematics for each runner throughout the stages discussed in **section.4.2** are presented. The focus is on the variation in the means and standard deviation of the parameters discussed in **section.3.2**. These results are discussed from an intra-subject point of view firstly. Secondly, they are discussed from and inter-subject point of view.

The presentation of the results is visually complemented by the graphs below. They show the evolution of the mean, minimal and maximal values of the most important parameters throughout the stages for each runner of the two datasets. A more detailed overview of the evolution of the mean and SD of each parameter is presented in the tables in the Appendix.

5.1 Intra-Subject Differences

The intra-subject differences in the variation of the parameters consists of the case by case analysis of the evolution of the different parameters between each stage with the objective of finding out the effects of different subject characteristics (gender, experience or velocity) on these parameters.

The evolution will be looked at in-between each stage for the 5+km run. The overall variation will also be analysed as it is indicative of the effect of the whole protocol.

Mean Peak Knee Flexion during Swing per Stride
Only two male subjects from the 5+km dataset show an overall statistically significant increase between all four stages. (See **fig.5**) The remaining three male subjects show an overall stable PKF swing that doesn't significantly change. These include the most experienced male runners with a mid-foot strike and a higher relative velocity than the others.

Four female subjects show an overall significant increase of the PKF swing. While the most experienced female, subject 7, shows an overall significant decrease in PKF swing. (See **fig.5**)

The PKF swing is stable for all runners of the 5+km during the fatigued run. There is only one exception that shows a significant increase after the fatiguing protocol and during the fatigued run. (See **fig.5**)

From the 8x400m run, three subjects showed a significant increase in mean PKF during swing per stride. While, two others showed a significant decrease in mean PKF swing. The two most experienced runners in this dataset, both forefroot runners with ten or more years of experience, showed no significant variation of the PKF swing. (See **fig.9**)

As expected, the PKF swing per stride shows a strong positive relationship with the velocity of running of the 5+km run. The value of the correlation factor is $R^2 Linear = 0.841$ for males and $R^2 Linear = 0.127$ for females.

Mean Peak Knee Flexion during Stance per Stride
Four male runners of the 5+km showed an overall significant increase in PKF stance between the four stages. For these runners, the increase happens during the "rested" run. The most experienced male runner, subject 2, shows a significant decrease in mean PKF stance between the 4 stages. (See **fig.6**)

The two most experienced female runners show no overall significant variation of the PKF stance. Meanwhile, two others show an overall significant increase and one subject a significant decrease. These variations happen during the "rested" run. (See **fig.6**)

All runners of the 5+km, except one, show no significant variation of the PKF stance during the fatigued run . (See **fig.6**)

For the 8x400m run, three runners showed a significant increase in mean PKF stance and three others a significant decrease. The remaining runner shows no significant variation. (See **fig.9**)

Mean Peak Hip Flexion during Swing per Stride
Two male runners of the 5+km show a significant overall increase of the PHF swing between the four stages. Two others show no significant overall variation, while subject 3 shows a significant overall decrease.

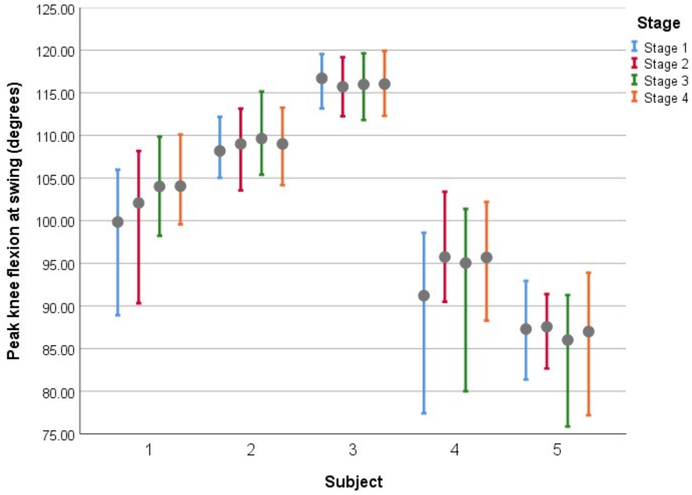
During the "rested" run, the first three male subjects show a significant decrease of the PHF swing with a subsequent significant increase after the fatiguing protocol. (See **fig.7**)

For the female runners, two subjects show a statistically significant overall increase of PHF swing. The two most experienced runners show a significant decrease in PHF swing in the meantime and only one runner shows no overall significant variation. (See **fig.7**)

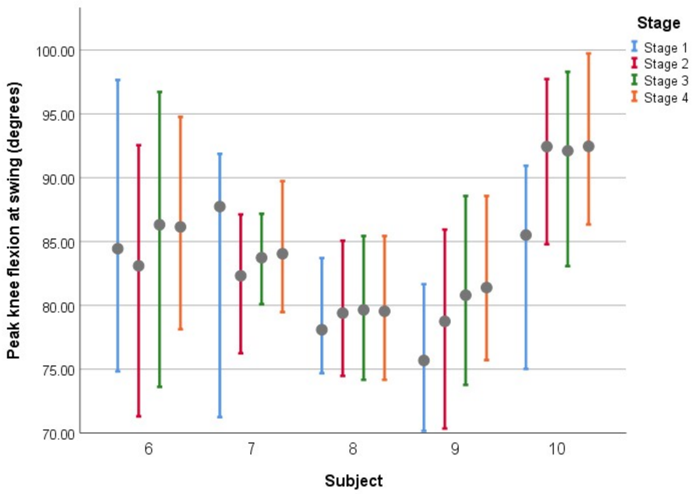
All subjects except runner 6 show a significant decrease in PHF swing between stages 1 and 2. Also, all runners except number 8 show a more or less significant increase after the fatiguing protocol.

All runners of the 5+km show no significant variation of the PHF swing during the fatigued run except the first subject that shows a significant increase. (See **fig.7**)

For the 8x400m run, an increase in PHF during swing was observed for all runner but subject 17 who showed a significant decrease. (See **fig.10**)

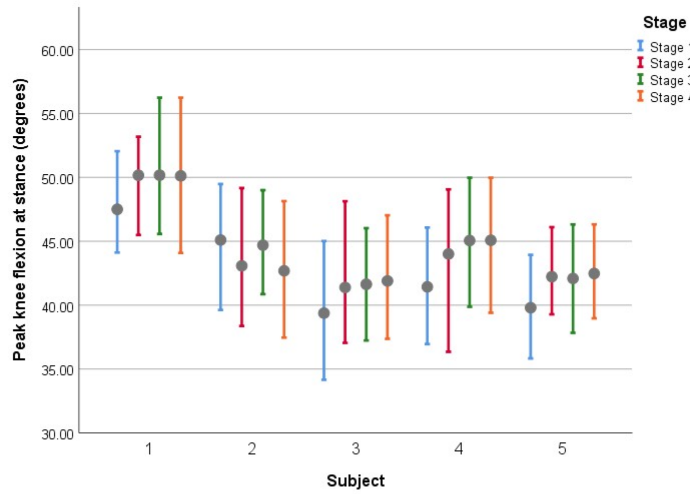


(a) PKF swing of males

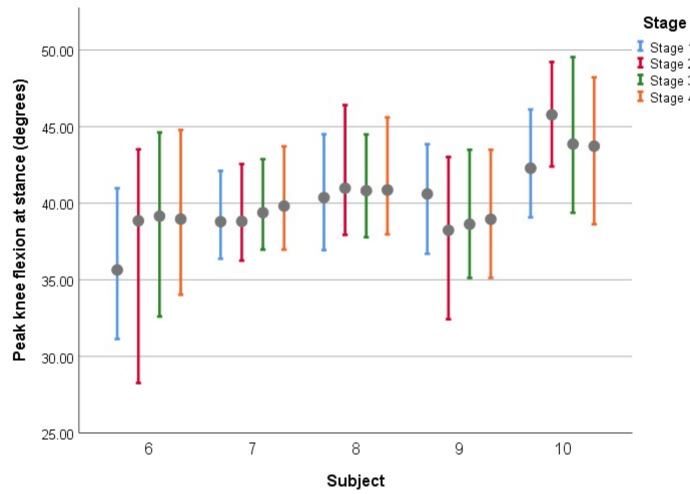


(b) PKF swing of females

Figure 5: Evolution of the mean peak knee flexion swing angle and its maximal and minimal values (a) per stage for the 5+km male runners and (b) per stage for the 5+km female runners.

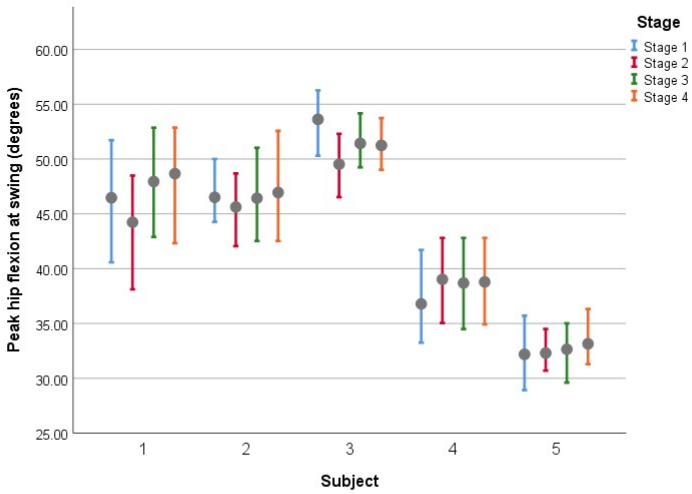


(a) PKF stance of males

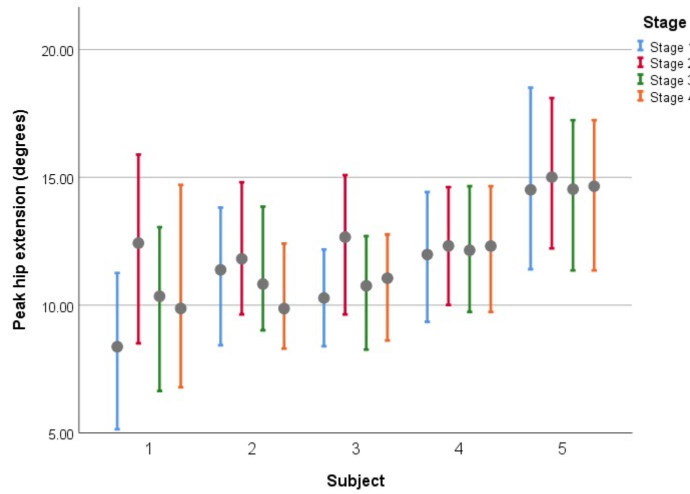


(b) PKF stance of females

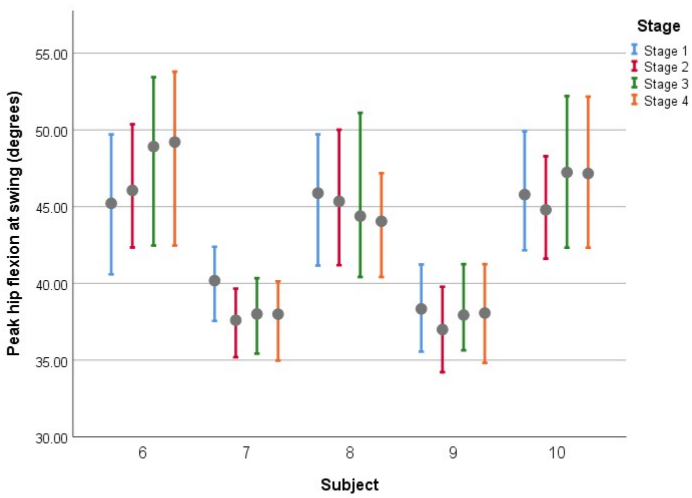
Figure 6: Evolution of the mean peak knee flexion stance angle and its maximal and minimal values (a) per stage for the 5+km male runners and (b) per stage for the 5+km female runners.



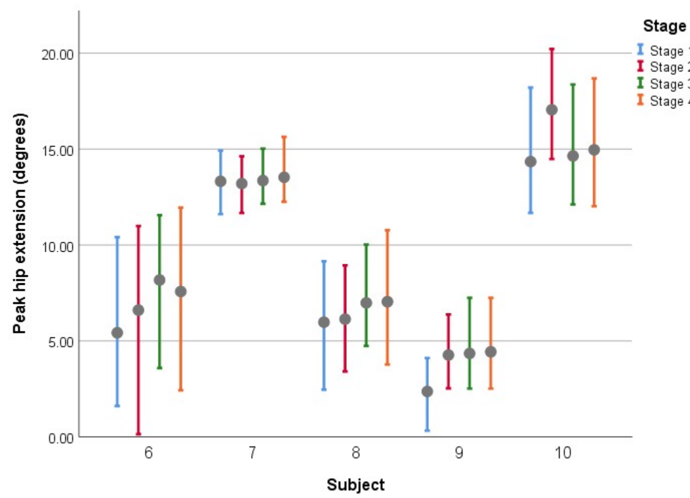
(a) PHF swing of males



(a) PHE of males



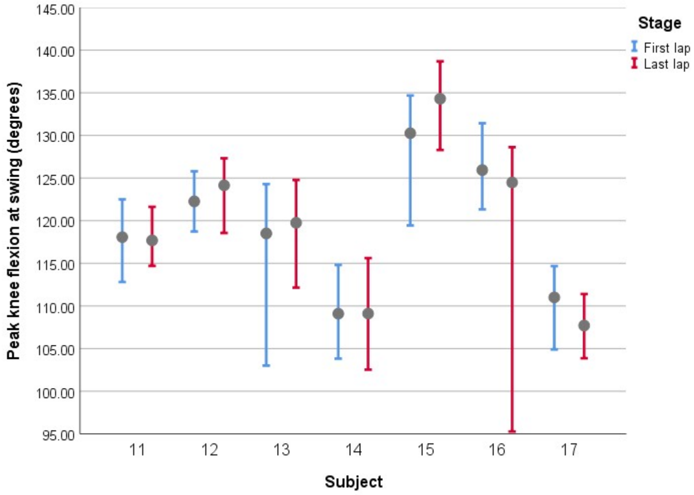
(b) PHF swing of females



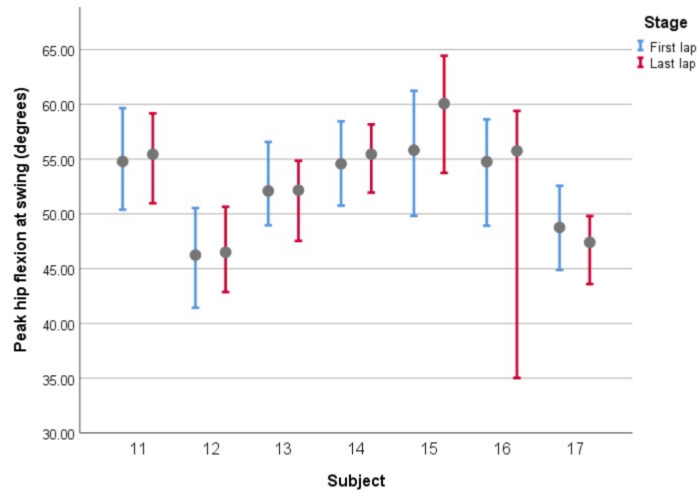
(b) PHE of females

Figure 7: Evolution of the mean peak hip flexion swing angle and its maximal and minimal values (a) per stage for the 5+km male runners and (b) per stage for the 5+km female runners.

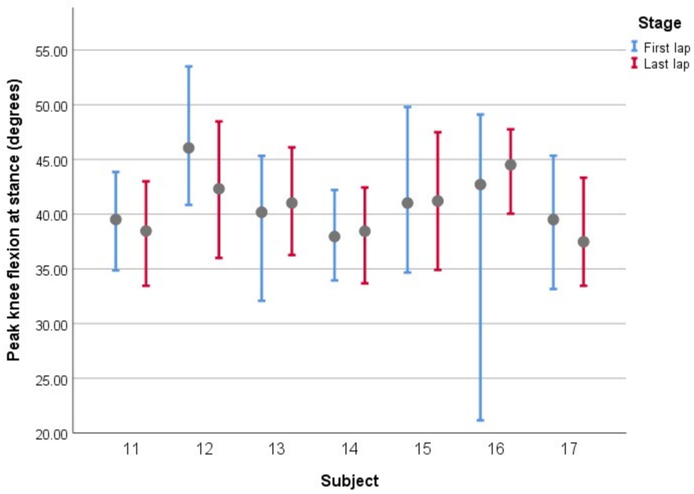
Figure 8: Evolution of the mean peak hip extension angle and its maximal and minimal values (a) per stage for the 5+km male runners and (b) per stage for the 5+km female runners.



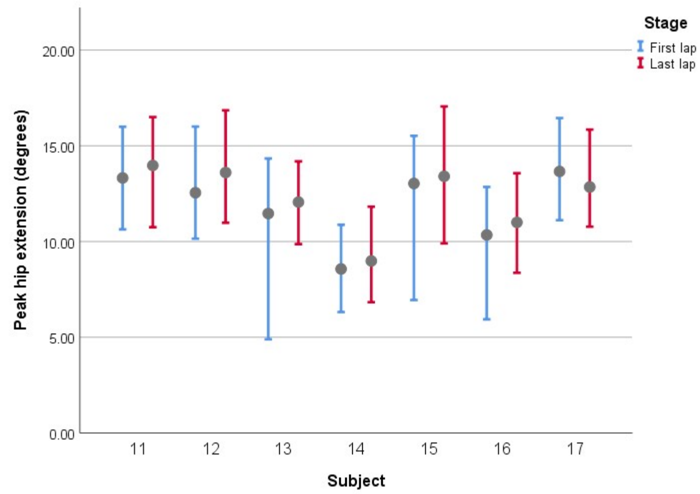
(a) PKF swing



(a) PHF swing



(b) PKF stance



(b) PHE

Figure 9: Evolution of the mean peak knee flexion angle at (a) swing and (b) stance and its maximal and minimal values between the first and last laps of the 8x400m run.

Figure 10: Evolution of the mean (a) hip flexion angle at swing and (b) hip extension just before toe-off and their maximal and minimal values between the first and last laps of the 8x400m run.

Mean Peak Hip Extension per Stride
Three male runners of the 5+km show no overall significant variation of the PHE. Meanwhile, subject 1 shows a significant overall increase and subject 2 shows a significant overall decrease. (See **fig.8**)

Nonetheless, all five male subjects show a significant increase between stages 1 and 2 of the PHE per stride. A subsequent more or less significant decrease is observed between stages 2 and 3 for all runners.

Three females subjects show an overall significant increase of the PHE during the 5+km run. The other two females show no overall significant variation of the PHE. (See **fig.8**)

During the "rested" run, three of the female runners show a significant increase of the PHE. The experienced subject 8 shows a significant increase only after the fatiguing protocol.

All runners of the 5+km show no significant variation of PHE during the fatigued run. (See **fig.8**)

Six out of the seven runners of the 8x400m showed a significant increase of the PHE between the first and last lap. Runner 17 is the only one to show a significant decrease in PHE. (See **fig.10**)

Mean Ankle Flexion at IC per Stride
Three male subjects of the 5+km run show an overall significant increase in AFIC per stride. This increase happens during the "rested" run for two of them. While for the experienced subject 3, the significant increase happens continuously over the 4 stages.

The most experienced male runner shows an overall significant decrease of AFIC that happens during the "rested" run, with a stabilization at the fatigued state. The least experienced runner in the set, subject 4, shows no significant variation of the mean AFIC between all 4 stages.

All female runners of the 5+km run, except the most experienced, show an overall significant increase in AFIC between all stages. Subject 7 shows an overall continuous significant decrease.

The significant increase in AFIC happens during the "rested" run for three of the female runners, with a subsequent decrease after the fatiguing protocol. Subject 9 only shows the significant increase after the fatiguing protocol.

The AFIC is stable during the fatigued run for all the runners of the 5+km. (See **table.5**)

For the 8x400m run, the AFIC of two runners decreases significantly between lap1 and lap8. The AFIC of subject 13 increased significantly. The others show an insignificant decrease of AFIC. (See **table.6**)

Stride Length and Frequency
Four subjects of the 5+km run show a significant decrease in SF in between two stages.

This significant decrease happens between stages 1 and 2 for three of them and is reflected by a significant increase in SL in between these two stages. The same can be said for subject 6 in between stages 2 and 3. (See **table.5**)

Even though the variations of SF and SL are statistically significant, these variation are minimal, in the order of a few centimetres.

5.2 Inter-Subject Differences

The inter-subject differences consists of the comparison of the different effects that the two runs, with different intensities and duration, have on the variation of the parameters of high interest (PKF swing and stance, PHF and PHE).

The comparison is limited to the most experienced male runners of the 5+km run (4 or more years of experience with a mid-foot strike pattern) since the runners in the 8x400m are all experienced male runners (4 or more years) that either show a mid-foot or a fore-foot strike. For this, subjects 2 and 3 have been chosen; It should be noted that they also show similar velocities to the ones in the 8x400m run ($\pm 5ms^{-1}$).

The PKF swing and stance both show contrasting results for the 8x400m run as discussed in the **section.5.1** above. The two runners from the 5+km show the same contrast. The PKF swing shows no significant variation for both and the PKF stance shows an increase for one and a decrease for the other.

Meanwhile, the PHE shows a significant increase for all but one runners of the 8x400m, this increase is also present for both selected runners of the 5+km, although only during the "rested" run with contrasting changes after the fatiguing protocol.

The mean peak hip flexion angle at swing per stride shows a more or less significant increase for all but one runners of the 8x400m run. Meanwhile, the two runners form the 5+km run both show a significant decrease of the PHF swing during the "rested" run, this trend reverses after the fatiguing protocol with a subsequent significant increase. Overall, subject 2 shows a significant decrease and subject 3 no significant change.

6 Discussion

The main objective of this paper was the quantification of fatigue induced by the intensity of running activities that were performed via the variations in lower leg kinematic parameters.

Some measured parameters show uniform variations for all subjects such as the peak hip flexion and extension, and others show contrasting results between subjects, like the peak knee flexion at swing, with some subjects showing significant variations in one direction (increase or decrease), others in the other direction and some showing no significant variation.

Below, the subject-by-subject results will be discussed with an analysis of the effects of personal characteristics on the variation of the parameters. This will be followed by the comparison of the effects of the intensity of the two different runs on these variations. Afterwards, conclusions will be drawn with the hope of answering the research question that was presented in **section.2**. Limitation to the study are discussed in the end.

6.1 Intra-Subject Differences

The mean peak knee flexion during swing per stride shows contrasting results for the 5+km run.

As opposed with the results of Chan-Roper et al. and Koblbauer et al., a significant increase is observable for only two males while the other three show insignificant variations of the PKF swing. [1] [10]

Female runners also show contrasting results with a significant decrease between stages 1 and 2 for two of them and a significant increase for the three others. Nonetheless, the PKF swing increases for female runners as fatigue sets in, especially in between stages 2 and 3 as discussed in the results, **section.5**.

The runners that show variations not in line with other subjects in the group set are those that have a higher running velocity, with runners 2, 3, 6 and 7 the fastest in their respective gender groups.

These contrasting results are also observable for the male runners of the 8x400m run with a significant increase for three runners and a significant decrease for two others. Again here, the most experienced runners in the set show no significant variation of the PKF swing as it is expected that more experienced runners show less significant variations than inexperienced ones.

The mean peak knee flexion during stance per stride shows results that are consistent for the 5+km run.

Four of the male runners showed a significant increase in PKF stance between stages 1 and 2. While the most experienced runner of the male subset showed a significant decrease throughout stages 1 to 4. These results are in line with those presented by Koblbauer et al.. [1]

Also, four female runners showed an increase in PKF stance between stages 1 and 2, with it only being insignificant for the most experienced. One female runner showed a significant decrease in the meantime.

The 8x400m run shows contrasting results with three experienced runners showing a significant increase between laps 1 and 8, three others showing a significant decrease and one runner, subject 15, the most experienced, showing no significant variation.

It is observed that the PKF at stance shows contrasting results with fatigue for experienced male runners, while inexperienced runners show an increase of PKF stance on average.

The mean peak hip flexion during swing per stride shows a significant decrease between stages 1 and 2 for three male runner of the 5+km run. For these runners, there is a subsequent significant increase that follows between stages 2 and 3. The overall increase in PHF swing between all four stages for most runners is in line with the results showed by Koblbauer et al. .

Four of the female runners show a significant decrease in PHF swing between stages 1 and 2. Only one runner shows a significant increase between those two stages. All the female runners except subject 8 show a subsequent increase in between stages 2 and 3, after the fatiguing protocol.

All runners of the 8x400m run show a significant increase in the PHF between the first and last lap except runner 17 that shows a significant decrease in between these two stages.

It could be inferred that the PHF during swing increases with fatigue for most subjects regardless of the experience or velocity of running. With most subjects showing an increase in PHF swing after the fatiguing protocol of the 5+km run. This is different than the PKF that usually shows a significant increase during the non-fatigued run, after which it stabilizes after reaching a "maximum".

There is an overall significant increase in peak hip extension just before toe-off for all runners of the 5+km except the most experienced male runner, subject 2, which shows a significant decrease.

All the male runners show a significant decrease after the fatiguing protocol. The PHE shows a stabilization at the fatigued state for all runners like the other parameters. These results can help understand the contrast between those of Chan-Roper et al. and Koblbauer et al., it could be deduced that the PHE increase with fatigue during a mid-distance run until a certain elevated level of fatigue is reached (comparable to the one at the end of a marathon run) after which it starts decreasing.

For the 8x400m run, all runners except one (similar to the PHF) show a significant increase in PHE between the first and last lap. The only exception is the most experienced runner that shows a non significant increase between these two stages.

It could be inferred that most runners, for mid-distance runs show a significant increase of PHE due to fatigue. This increase is present but not significant at the 0.05 level for the most experienced runners of the datasets.

For the ankle flexion angle at initial contact most runners of the 5+km dataset show a significant increase in between stages 1 and 2.

The two most experienced runners of the 5+km run show a significant decrease between the first three stages.

Five of the seven experienced runners of the 8x400m run show a more or less significant decrease in AFIC in between laps 1 and 8. Meanwhile, one runner shows a significant increase and another an insignificant one.

It could be assumed that inexperienced runner generally show a significant increase in AFIC, like those in the 5+km run and runner 13 of the 8x400m run. While experienced runners tend to show a significant decrease in AFIC as is the case with most 8x400m runners and the two most experienced runners of the 5+km run.

The stride length and frequency generally show no variations for the 5+km run as the velocity is maintained constant and there was no need to alter any of these parameters in order to alter the velocity of running. Some runners show a significant decrease of the SF, and a resulting increase of the SL, in between stage 1 and 2 or 2 and 3 as the fatigued state is reached. These are the inexperienced ones such as runners 4, 5 and 6.

For the 8x400m run, the step length and frequency were measured instead but results show contradictions as an increase in SF was always accompanied by an increase in SL which invalidates these parameters for this dataset.

Stability during Fatigued Run
For all subjects of the 5+km run, the parameters show no significant variation during the fatigued run, this could be explained using the observed Borg scale evolution with the runners expressing peak levels of exertion that don't, or minimally, vary in between stages 3 and 4, thus the fatigue levels of the runners already reached a maximal heavy state that is reflected in the lack of variation of the parameters.

6.2 Inter-Subject Differences

Mean Peak Knee Flexion during Swing per Stride
By comparing the average change for all runner of the male subjects in each dataset as they are shown in **table.3**, the PKF swing shows an average increase of 3.2% between the fatigued and non-fatigued states for males in the 5+km run, this is in line with results by Chan-Roper et al.. [10] Meanwhile this increase is pretty much insignificant at 0.2% for the 8x400m run. This could be attributed with the higher velocity at which the 8x400m is run as the faster male runners in the 5+km run also show no significant variation of the PKF at swing.

Mean Peak Knee Flexion during Stance per Stride
For the males of the 5+km run, there is an average increase of PKF stance of 4.7% between the fatigued and non-fatigued states, while the experienced runners of the 8x400m run show results in line with those of Chan-Roper et al. with a decrease of PKF stance of 1.3%. [10]

Mean Peak Hip Flexion Angle during Swing per Stride
On average, there is an increase in PHF during swing of 2% for male runners of the 5+km, of 0.5% for the females and of 1.5% for the experienced 8x400m runners.

Mean Peak Hip Extension
The 5+km runners show a significant average increase of PHE between fatigued and non fatigued state, 2.5% for the males and 15.4% for the females. The 8x400m runners show a much less significant increase of 3.5%.

It can be inferred that the increase in PHE with fatigue is more significant for female runners than for male runners in mid-distance runs such as the 5+km one.

Mean Ankle Flexion Angle at Initial Contact
The 5+km runners show an overall increase in AFIC with an average significant increase of 5.7% for the male runners and a significant increase of 5.9% for the females. The runners of the 8x400m run show an average significant decrease of 21.8%, this could be due to the influence of runner 12 that shows a very pronounced decrease of 202.2% that could be attributed to an error in measurement or processing.

6.3 Effect of the Intensity of the Runs on Lower Leg Kinematic Parameters

By restricting the analysis to runners that show the same characteristics with regards to velocity, gender and experience, as discussed in **section.5.2**, inferences are made on the effect of the intensity and duration of the runs on the variation of the parameters of interest.

It was observed that the runners from the 8x400m run and the two selected runners from the 5+km run show the same contrasts in variation of the PKF swing and stance. They also show the same overall increase in PHE. Meanwhile, the increase in PHF swing shown by the 8x400m runners only appears after the fatiguing protocol for the two 5+km runners. One of them shows an overall decrease in PHF swing, and the other an overall stable PHF swing.

It can be interpreted that, the higher intensity of the 8x400m run causes no alteration in the variation of the PKF swing and stance and of the PHE. Nonetheless, the superior intensity of the 8x400m run causes an increase in the PHF swing that sets in earlier than for the experienced runners of the 5+km run.

6.4 Effect of Fatigue on Lower Leg Kinematic Parameters

From the intra-subject and inter-subject analyses, conclusions are drawn in this section about the effect that fatigue has on the lower-leg kinematic of runners in the sagittal plane.

A number of papers, such as the ones by Winter el al., Chan-Roper et al. and Reenalda et al., have discussed how the kinematic alterations due to fatigue that are presented in this section have an affect on the running performance and economics. They also analysed the possible injury risks that are directly and indirectly caused by the alterations that arise with fatigue. [4] [10] [11]

Effect of Fatigue on PKF Swing
Contrasting results for male runners in both datasets allow for the inference that fatigue doesn't directly influence the PKF swing in male runners.

Meanwhile, female runners mostly showed a significant increase in PKF swing between stages (as discussed in the **section.6.1** above) that allow for the deduction that the PKF swing increases significantly due to fatigue for females in mid-distance runs. This increase is more pronounced for inexperienced runners.

Winter et al. and Chan-Roper et al. discussed how the increase in PKF swing with fatigue improves the running economy as the it causes a decrease in the moment of inertia of the lower limbs around the hip joint thus supporting an "ease" of the swing phase. [4] [10]

Effect of Fatigue on PKF Stance
As presented in the intra-subject discussion, the PKF stance significantly increases with fatigue for inexperienced runners, while experienced runners mostly show contrasting results.

Even though the runners of the 8x400m run show an overall average decrease in PKF stance, this can not be taken as a given since half the runners show a significant increase and the other a significant decrease. This goes as well for the experienced runners in the 5+km dataset.

Winter et al. and Reenalda et al., suggest that the alterations in knee flexion during stance in general is part of an adaptive strategy to maintain the shock attenuation performed by the body as the Peak Tibial Acceleration was found to increase with fatigue. [3] [4] [11]

Inexperienced runners generally show an increase in PKF stance as part of the adaptive strategy. Meanwhile, experienced runners could show this behavior but it can not be generalized to all of them.

Effect of Fatigue on PHF Swing
From the intra-subject analysis, it can be inferred that, overall the PHF swing significantly increases for inexperienced runners in mid-distance runs and significantly decreases for experienced runners due to fatigue. Nonetheless, the PHF swing was decreasing for all the runners during the rested run with the subsequent increase, as the fatigue levels increased, affecting lower experienced runners more significantly for them to show an overall increase.

Meanwhile in more intense runs, like the 8x400m one, experienced runners show an overall significant increase in PHF swing due to fatigue.

Effect of Fatigue on PHE
All runners, no matter the experience or intensity showed an overall significant increase in PHE with fatigue.

For male runners of the 5+km, the PHE reached a certain ceiling after which a decrease followed. For the female runners, the PHE continued to increase with fatigue throughout all stages of the run. The increase in PHE is thus much more significant for females than males performing the same mid-distance running activity as discussed in the **section.6.2** above.

Chan-Roper et al. suggest that the variations in the movement of the hip could be attributed to the increase in trunk forward lean. It has been proved to happen with fatigue, by Strohrmann et al., although much less significantly for experienced runners. [10] [16]

Effect of Fatigue on AFIC
Experienced male runners from both datasets showed an overall decrease in AFIC due to fatigue. Meanwhile, inexperienced male and female runners showed a significant increase of AFIC with fatigue during the 5+km run.

Strohrmann et al. and Larson et al. discussed how runners typically tend to show a more heel-strike like behaviour of the foot as fatigue settled in. This behaviour is much more visible with inexperienced runners and can be seen in this research as the ankle flexion increased with fatigued for inexperienced runners. [16] [17]

Effect of Fatigue on SF and SL
The results of this study didn't show any significant variation of SF or SL that came with fatigue during a run. This could be explained by the constant velocity at which the runs were performed as the variation of SF and SL are mainly done with the objective of altering the velocity of running by changing one of them as fatigue sets in.

6.5 Limitations and Recommendations

The main limitation to the study was that the datasets consisted of a restricted number of runners with 5 male and 5 female subjects for the 5+km and 7 male subjects for the 8x400m run. This meant that it was hard to divide the runners in further subgroups, such as experienced male runners from the 5+km set for the inter-subject analysis. The small sample size also means that the results and conclusions can not be taken as a definitive truth and can not be extrapolated for all types of runners and runs.

To remedy to this, the same running "tasks" could have been performed on the same group of runners as it could have allowed to draw more conclusive results on the effects of the different intensities of the runs.

Another limitation that was discussed in the paper is that the one-way ANOVA statistical tool that was used didn't have all the conditions to its use satisfied. It is nonetheless a test that is robust against the violation of one or more of these assumptions and was therefore used as it was hard to find a good alternative for the specific analysis that was done. [18]

7 Conclusion

The objective of this study was to analyse the effect of fatigue on the lower leg kinematics of runners. This was done via the intra and inter-subject analysis of the variation of sagittal plane angles of different dominant-leg parts at different stages of mid-distance runs. The effects of the gender, experience and velocity of the runners on the variation of the parameters were also analysed.

The main finding of this paper is that fatigue has a direct effect on some parameters that were considered. Such as the PKF swing that increases for female runners, the PKF stance that increases with inexperienced runners, the PHF swing that increases for experienced runners performing intense runs, the PHE just before TO that increases for all runners no matter the experience and the AFIC that shows a significant increase for inexperienced runners and a significant decrease for experienced runners.

These variations due to fatigue are limited in the sense that they will not continue as long as the runner is fatigued, or shows an increase in fatigue. All parameters show a stabilization during the fatigued run of the 5+km as if a certain threshold has been reached that the parameters will not overpass.

Other findings, related to the runners' personal traits are that faster runners show much less variation in PKF swing than slower ones. Female runners show a much more significant increase in PHE than their male counterparts and experienced runners tend to show a much less significant variation in any parameter with fatigue than inexperienced ones.

By comparing the intensity of the two runs that were performed, it was also observed that the higher intensity of the 8x400m run influences the variation of PHF swing. It shows an overall increase in between fatigued and non-fatigued state. This is opposed to the 5+km run that shows an overall significant decrease in between fatigued and non-fatigued state. With the increase only happening after a certain fatigue threshold has been reached. Nonetheless, it is not significant enough to change the overall direction of change of this parameter.

References

[1] Ian F. Koblbauer et al., "Kinematic changes during running-induced fatigue and relations withcore endurance in novice runners", Journal of Science and Medicine in Sport, 2013.

[2] R.Enoka, Jacques Duchateau, "Translating Fatigue to Human Performance", 2016.

[3] Reenalda, J., et al., Continuous three dimensional analysis of running mechanics during a marathon by means of inertial magnetic measurement units to objectify changes in running mechanics, Journal of Biomechanics, 2016.

[4] S.Winter et al., "Effects of fatigue on kinematics and kinetics during overground running: a systematic review", The Journal of Sports Medicine and Physical Fitness 2017 June; 57(6):887-99.

[5] Xsens Technologies B.V., "MVN User Manual", 2020.

[6] M.Schepers et al., "Xsens MVN: Consistent Tracking of Human Motion Using Inertial Sensing", XSENS TECHNOLOGIES B.V. .

[7] M.Paulich et al., "Xsens MTw Awinda: Miniature Wireless Inertial-Magnetic Motion Tracker for Highly Accurate 3D Kinematic Applications", XSENS TECHNOLOGIES B.V. .

[8] H.G.Chambers & D.H.Sutherland, "A Practical Guide to gait Analysis", The Journal of the American Academy of Orthopaedic Surgeons, May 2002.

[9] The Motion Mechanic, "The Biomechanic of Running: 3 Common Technique Faults", 2019.

`http://www.themotionmechanic.com/2019/02/20/the-biomechanics-of-running-3-common-technique-faults/`

[10] M.Chan-Roper et al., "Kinematic Changes During a Marathon for Fast and Slow Runners", Journal of Sports Science and Medicine, March 2012.

[11] J.Reenalda et al., "Kinematics and shock attenuation during a prolonged run on the athletic track as measured with inertial magnetic measurement units", Gait and Posture 68, 2019.

[12] R.Williams et al., "Changes in Distance Running Kinematics With Fatigue", International Journal of Sport Biomechanics, 1991.

[13] G.Borg, "Borg's Perceived Exertion And Pain Scales", Chapter 5, 1998.

[14] Raquel Garzon, "Why and How to Do Aerobic Training, Including High-intensity Interval Training", Guide I-112, College of Agricultural, Consumer and Environmental Sciences, New Mexico State University, 2018.

`https://aces.nmsu.edu/pubs/_i/I112/welcome.html`

[15] One-way ANOVA in SPSS Statistics, Lund Research Ltd, 2018.

`https://statistics.laerd.com/spss-tutorials/one-way-anova-using-spss-statistics.php#:~:text=The%20one%2Dway%20analysis%20of,%2C%20rather%20than%20two%20groups).`

[16] C.Strohrmann et al., "Monitoring Kinematic Changes With Fatigue in Running Using Body-Worn Sensors", 2012.

[17] P. Larson et al.: Foot strike patterns of recreational and sub-elite runners in a long-distance road race, Journal of Sports Sciences, 29:15, 1665-1673, 2011.

[18] "Does your data violate one-way ANOVA assumptions?", Quality Control Plan.

`https://quality-control-plan.com/StatGuide/oneway_anova_ass_viol.htm#:~:text=Outliers%20are%20anomalous%20values%20in,of%20rejecting%20the%20null%20hypothesis.&text=Apparent%20outliers%20may%20also%20be,same%2C%20but%20nonnormal%2C%20population.`

8 Appendix

	Mean Peak Knee Flexion Swing				Mean Peak Knee Flexion Stance			
	5+km Run - Males							
Subject	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
1	99.85 ± 2.27	$102.08 \pm 2.41^*$	$104.01 \pm 2.28^*$	104.05 ± 2.15	47.5 ± 1.5	$50.16 \pm 1.48^*$	50.17 ± 1.76	50.12 ± 1.96
2	108.18 ± 1.58	109 ± 1.93	109.63 ± 2.06	109 ± 2	45.10 ± 2.17	$43.08 \pm 2.26^*$	$44.69 \pm 1.89^*$	$42.69 \pm 2.03^*$
3	116.7 ± 1.33	115.71 ± 1.18	115.98 ± 1.43	116.03 ± 1.59	39.37 ± 1.98	$41.38 \pm 2.11^*$	41.63 ± 2.06	41.89 ± 1.98
4	91.21 ± 3.03	$95.74 \pm 2.15^*$	95.04 ± 2.79	95.69 ± 2.37	41.43 ± 1.65	$44.01 \pm 2.09^*$	$45.05 \pm 2.00^*$	45.07 ± 2.03
5	87.29 ± 2.05	87.55 ± 1.46	86 ± 2.74	87 ± 2.04	39.80 ± 1.60	$42.23 \pm 1.25^*$	42.09 ± 1.42	42.47 ± 1.21
Average	98.86 ± 10.71	100.43 ± 9.86	100.45 ± 10.78	100.75 ± 10.25	42.59 ± 3.59	44.29 ± 3.62	44.82 ± 3.55	44.61 ± 3.54
	5+km Run - Females							
Subject	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
6	84.44 ± 3.5	$83.09 \pm 2.61^*$	$86.32 \pm 2.96^*$	86.15 ± 3.16	35.64 ± 2.28	$38.85 \pm 1.61^*$	39.16 ± 2.10	38.96 ± 2.37
7	87.74 ± 2.57	$82.31 \pm 1.42^*$	$83.73 \pm 1.38^*$	84.04 ± 1.7	38.80 ± 1.31	38.81 ± 1.08	39.38 ± 1.07	39.81 ± 1.13
8	78.09 ± 1.39	$79.39 \pm 1.79^*$	79.65 ± 1.85	79.54 ± 1.84	40.37 ± 1.14	$40.98 \pm 1.26^*$	40.82 ± 1.32	40.86 ± 1.31
9	75.68 ± 1.94	$78.74 \pm 2.31^*$	$80.79 \pm 2.39^*$	$81.39 \pm 2.03^*$	40.61 ± 1.44	$38.23 \pm 1.62^*$	38.63 ± 1.27	38.95 ± 1.20
10	85.5 ± 2.25	$92.44 \pm 1.68^*$	92.11 ± 2.13	92.45 ± 1.98	42.28 ± 1.17	$45.77 \pm 1.29^*$	$43.86 \pm 1.48^*$	43.72 ± 1.58
Average	82.01 ± 5.21	83.17 ± 5.4	84.46 ± 5.05	84.67 ± 5.07	39.63 ± 2.69	40.59 ± 3.14	40.4 ± 2.42	40.49 ± 2.39

Table 3: Mean peak knee flexion during swing and stance phases per stride at different stages of the 5+km run. An * indicates a significant change with respect to the previous stage at a significance level of $p < 0.05$.

	Mean Peak Hip Flexion Swing				Mean Peak Hip Extension			
	5+km Run - Males							
Subject	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
1	46.46 ± 1.98	$44.23 \pm 1.88^*$	$47.95 \pm 1.94^*$	$48.67 \pm 1.90^*$	8.37 ± 1.10	$12.43 \pm 1.24^*$	$10.35 \pm 1.17^*$	9.87 ± 1.35
2	46.51 ± 1.02	$45.62 \pm 1.22^*$	$46.43 \pm 1.40^*$	46.94 ± 1.53	11.38 ± 1.08	$11.81 \pm 0.88^*$	$10.83 \pm 0.88^*$	$9.87 \pm 0.82^*$
3	53.62 ± 1.11	$49.53 \pm 1.31^*$	$51.42 \pm 1.07^*$	51.24 ± 0.97	10.28 ± 1.06	$12.66 \pm 1.03^*$	$10.76 \pm 0.92^*$	11.05 ± 0.93
4	36.79 ± 1.53	$39.03 \pm 1.51^*$	38.69 ± 1.65	38.79 ± 1.57	11.98 ± 0.99	$12.32 \pm 0.89^*$	12.15 ± 0.86	12.31 ± 0.86
5	32.19 ± 1.07	32.30 ± 0.84	32.65 ± 1.01	33.15 ± 0.83	14.51 ± 1.37	$15.01 \pm 1.15^*$	$14.54 \pm 1.23^*$	14.65 ± 1.09
Average	41.94 ± 7.73	41.25 ± 6.14	42.45 ± 7.05	42.79 ± 6.99	11.47 ± 2.4	12.95 ± 1.58	11.90 ± 1.9	11.76 ± 2.13
	5+km Run - Females							
Subject	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
6	45.21 ± 1.42	$46.06 \pm 1.62^*$	$48.91 \pm 1.61^*$	49.21 ± 1.89	5.42 ± 1.56	$6.61 \pm 1.67^*$	$8.18 \pm 1.51^*$	7.58 ± 1.56
7	40.18 ± 0.93	$37.60 \pm 0.87^*$	38.01 ± 0.90	37.99 ± 0.91	13.32 ± 0.65	13.20 ± 0.54	13.36 ± 0.61	13.53 ± 0.65
8	45.88 ± 1.23	$45.34 \pm 1.48^*$	$44.38 \pm 1.38^*$	44.05 ± 1.3	5.98 ± 1.05	6.14 ± 1.05	$6.98 \pm 1.00^*$	7.04 ± 1.15
9	38.34 ± 0.89	$36.99 \pm 1.01^*$	$37.94 \pm 1.05^*$	38.07 ± 0.96	2.37 ± 0.65	$4.27 \pm 0.69^*$	4.35 ± 0.71	4.43 ± 0.74
10	45.78 ± 1.31	$44.79 \pm 1.44^*$	$47.23 \pm 1.67^*$	47.16 ± 1.63	14.35 ± 1.03	$17.05 \pm 1.03^*$	$14.64 \pm 1.12^*$	14.96 ± 1.23
Average	43.1 ± 3.43	42.19 ± 4.2	43.32 ± 4.74	43.32 ± 4.77	8.11 ± 4.84	9.32 ± 5.02	9.35 ± 4.07	9.36 ± 4.22

Table 4: Mean peak hip flexion during swing and mean peak hip extension before toe-off per stride at different stages of the 5+km run. An * indicates a significant change with respect to the previous stage at a significance level of $p < 0.05$.

	Mean Ankle Flexion Angle Initial Contact				Mean Stride Frequency			
				5+km Run - Males				
Subject	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
1	13.98 ± 1.91	15.92 ± 2.06*	15.34 ± 2.08	15.22 ± 1.91	1.48 ± 0.03	1.43 ± 0.02*	1.41 ± 0.03	1.41 ± 0.02
2	17.69 ± 5.02	15.23 ± 4.99*	15.47 ± 5.21	15.34 ± 4.92	1.54 ± 0.02	1.54 ± 0.02	1.54 ± 0.02	1.54 ± 0.02
3	6.31 ± 3.30	7.17 ± 3.81	8.27 ± 3.73*	8.53 ± 4.09	1.54 ± 0.03	1.56 ± 0.02	1.56 ± 0.02	1.56 ± 0.02
4	12.11 ± 2.64	12.21 ± 2.87	12.28 ± 2.76	12.30 ± 2.60	1.38 ± 0.02	1.34 ± 0.02*	1.34 ± 0.02	1.34 ± 0.02
5	11.47 ± 2.00	14.04 ± 2.22*	13.24 ± 2.07*	13.32 ± 2.29	1.30 ± 0.02	1.30 ± 0.02	1.30 ± 0.02	1.30 ± 0.02
Average	12.36 ± 4.51	13.12 ± 4.31	13.04 ± 4.01	13.06 ± 3.92	1.43 ± 0.1	1.42 ± 0.1	1.41 ± 0.1	1.41 ± 0.1
				5+km Run - Females				
Subject	Stage 1	Stage 2	Stage 3	Stage 4	Stage 1	Stage 2	Stage 3	Stage 4
6	8.12 ± 1.81	11.11 ± 1.76*	10.20 ± 2.15*	9.78 ± 1.90	1.46 ± 0.04	1.45 ± 0.04	1.40 ± 0.03*	1.41 ± 0.03
7	13.65 ± 2.42	12.55 ± 2.35*	11.37 ± 2.26*	11.73 ± 2.29	1.46 ± 0.02	1.47 ± 0.03	1.47 ± 0.03	1.47 ± 0.03
8	4.11 ± 1.36	4.94 ± 1.69*	4.21 ± 1.85*	4.70 ± 1.75*	1.36 ± 0.02	1.36 ± 0.02	1.36 ± 0.03	1.36 ± 0.03
9	10.81 ± 1.09	10.63 ± 1.30	11.57 ± 1.34*	11.74 ± 1.33	1.31 ± 0.02	1.32 ± 0.02	1.31 ± 0.02	1.31 ± 0.02
10	15.71 ± 2.71	17.59 ± 2.85*	17.14 ± 3.01	17.20 ± 3.19	1.36 ± 0.03	1.34 ± 0.02*	1.34 ± 0.02	1.33 ± 0.02
Average	10.41 ± 4.56	11.31 ± 4.61	10.88 ± 4.73	11.02 ± 4.63	1.39 ± 0.07	1.38 ± 0.07	1.37 ± 0.06	1.37 ± 0.06

Table 5: Mean ankle flexion angle at IC per stride and mean stride frequency at different stages of the 5+km run. An * indicates a significant change with respect to the previous stage at a significance level of $p < 0.05$.

					8x400m Run					
Subject	PKFSwing		PKFStance		PHFSwing		PHE		AFIC	
	Lap1	Lap8	Lap1	Lap8	Lap1	Lap8	Lap1	Lap8	Lap1	Lap8
11	118.07 ± 1.49	117.68 ± 1.55	39.51 ± 1.48	38.46 ± 1.79*	54.78 ± 1.94	55.44 ± 1.56*	13.32 ± 1.04	13.97 ± 1.12*	7.62 ± 3.94	6.92 ± 4.52
12	122.26 ± 1.56	124.15 ± 1.38*	46.06 ± 2.19	42.32 ± 2.24*	46.24 ± 2.09	46.49 ± 1.62	12.55 ± 1.19	13.60 ± 1.19*	11.06 ± 4.60	3.66 ± 4.96*
13	118.50 ± 2.52	119.75 ± 2.01*	40.18 ± 2.37	41.02 ± 2.21*	52.09 ± 1.51	52.16 ± 1.26	11.46 ± 1.43	12.06 ± 0.87*	7.14 ± 2.74	8.14 ± 2.32*
14	109.09 ± 2.30	109.11 ± 2.37	37.95 ± 1.73	38.44 ± 1.47*	54.57 ± 1.70	55.45 ± 1.27*	8.57 ± 1.04	8.99 ± 1.07*	4.19 ± 5.90	4.23 ± 5.20
15	130.26 ± 2.43	134.30 ± 2.04*	41.02 ± 2.78	41.20 ± 2.44	55.81 ± 2.05	60.07 ± 2.05*	13.03 ± 1.44	13.40 ± 1.51	8.49 ± 3.09	7.66 ± 3.42
16	125.93 ± 2.02	124.48 ± 3.78*	42.71 ± 5.06	44.51 ± 1.85*	54.76 ± 1.99	55.75 ± 3.15*	10.34 ± 1.31	11.00 ± 0.92*	8.70 ± 3.38	8.46 ± 3.16
17	111.00 ± 1.75	107.70 ± 1.65*	39.50 ± 2.56	37.48 ± 1.73*	48.76 ± 1.38	47.40 ± 1.11*	13.66 ± 1.07	12.85 ± 0.72*	13.60 ± 4.78	11.10 ± 5.05*
Average	119.17 ± 7.35	119.43 ± 8.88	40.99 ± 3.76	40.46 ± 3.06	52.39 ± 3.84	53.18 ± 4.89	11.84 ± 2.12	12.25 ± 1.97	8.71 ± 5.05	7.15 ± 4.87

Table 6: Mean peak knee flexion during swing and stance, peak hip flexion and extension and ankle flexion at IC per stride at the first and last lap of the 8x400m run. An * indicates a significant change with respect to the first lap at a significance level of $p < 0.05$.